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EXPLORING A COMPLEX ADAPTIVE SYSTEMS APPROACH TO THE STUDY OF URBAN CHANGE

by

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Dissertation submitted in fulfilment of the requirements for the degree Master of Town and Regional Planning in the Faculty of Engineering, Built Environment and Information Technology, University of Pretoria

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Prof Karina Landman & Prof Chrisna du Plessis

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DECLARATION OF ORIGINALITY

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Declaration

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In order to test some of the concepts within this dissertation and to develop them further some of the contents may be found in the following[1]:

Nel, D., Landman, K., 2015. Gating in South Africa: A gated community is a tree; a city is not, in: Bagaeen, S., Uduku, O. (Eds.), Beyond Gated Communities. Routledge, London.

Landman, K., Nel, D., 2013. A Gated Community is a Tree; a City is Not, in: Transitional Spaces and Appropriation Strategies (from the Point of View of Morphology, Architecture, Design and Political Sciences). Proceedings of the 7th International Conference for Gated Communities and Private Urban Governances, University of Brighton, University of Brighton Moulsecoomb Campus, UK.

Landman, K., Nel, D., 2013. Exploring The Relationship Between Urban Morphology and Resilience In A Few Neighbourhoods In Pretoria, in: Spatial Considerations and Resilient Urban Form. Proceedings of the 2nd National Urban Design Seminar, The Villa, Pretoria.

Nel, D., Plessis Du, C., Landman, K., 2013. Exploring a Methodological Framework for Understanding Adaptive Change in Cities, in: Kajewski, S., Manley, K., Hampson, K. (Eds.), Disasters and the Built Environment. Proceedings of The 19th CIB World Building Congress, Brisbane 2013: Construction and Society, Queensland University of Technology, Brisbane Convention Centre, Brisbane, Australia.

Landman, K., Nel, D., 2012. Reconsidering urban resilience through an exploration of the historical system dynamics in two neighbourhoods in Pretoria, in: Spatial Planning: Promoting Resilience and Sustainability of Settlements. Proceedings of the Planning Africa Conference 2012, Durban, South Africa.

[1] More detail about these publications can be seen in Annexure 1

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Nel, V., Nel, D., 2012. An Exploration into Urban Resilience from a Complex Adaptive Systems Perspective, in: Spatial Planning: Promoting Resilience and Sustainability of Settlements. Proceedings of the Planning Africa Conference 2012, Durban, South Africa.

Nel, D., 2011. What Drives Spatial Change within a Neighbourhood? (Honours Dissertation). University of Pretoria, Pretoria.

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SUMMARY

Cities are one of humankind's more enduring creations. Although historically cities have perished, urbanism has not; declining urban areas have either revived or new cities have taken their place. Additionally, with the increasing rate of urbanisation cities have not only increased in number but also in size, while simultaneously their impact on the environment has grown, giving rise to debate on the sustainability of cities. However, this becomes a difficult task given that our cities are experiencing unprecedented challenges, of rapid urbanisation, strained and aging infrastructure, social unrest, and the increasing impacts and concerns of climate change. The need for cities to adapt or die has never been greater. The concept of resilience presents a possible solution to help deal with this unpredictable nature of the future. It refers to a system's (a city for example) ability to withstand sudden shocks, like floods, while at the same time having the capacity to adapt to long-term, incremental, changes, like climate change and global warming.

As the concept of resilience has become ever more popular within the scientific and planning community, the need to understand this concept and its implications is becoming more important. However, to do this we must first take a step back and understand the theoretical principles/foundations on which resilience theory has been built. Resilience is an emergent property of complex adaptive systems (CAS). Thus, to understand resilience, we must first understand CAS. Complexity theory seeks to understand how complex systems work. One of the ways that complexity theory does this is by understanding properties and mechanisms that allow complex systems to function and survive. Cities can be described as complex adaptive systems as they are undeniably complex and exhibit the same properties that can be found in any CAS.

Through the study of social-ecological systems (SES), which are also CAS, researchers have identified that social-ecological systems go through periodic cycles of change, each cycle with its own identifiable characteristics. These cycles of change have been described through the concepts of 'Panarchy' and the 'Adaptive Cycle'. This study seeks to apply these concepts to the study of urban change in an attempt to test their usefulness in understanding the urban system and how it changes.

The concepts from complexity theory and SES theory have been brought together and presented in this study in the form of a framework. The aim of the framework is to describe the urban system and how it changes. The proposed framework has potential to be both a useful theoretical construct and, with some adaptions, a useful tool or manual for practitioners in the field who need to make sense of the complex environments in which they find themselves. It is expected that the framework will become another instrument in a planner's toolbox by means of which they can make better informed decisions.

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There are a number of people without whom this study would not have been possible. I am tremendously grateful to them.

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LIST OF ABBREVIATIONS

AC – Adaptive cycle

CAS – Complex Adaptive System

CBD – Central Business District

GIS – Geographic Information System

GST -General systems theory

IDP – Integrated Development Plan

SACN – South African Cities Network

SDF – Spatial Development Framework

SES – Social-ecological System

SPULMA – Spatial Planning and Land Use Management Act

UCF – Urban change framework

USDF – Urban systems description framework

UN- Habitat – United Nations Human Settlements Programme

UNESCAP - United Nations Economic and Social Commission for Asia and the Pacific

UNISDR – United Nations Office for Disaster Risk Reduction

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Chaper 1: Introduction to the study

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1.1. Introduction

Cities are one of mankind's more enduring creations. Although historically cities have perished, urbanism has not; declining urban areas have either revived or new cities have taken their place. Moreover, with the increasing rate of urbanisation cities have not only increased in number but also in size, while at the same time their impact on the environment has grown, giving rise to debate on the sustainability of cities. Given the goals of sustainability, cities are faced with a difficult task, in that cities are experiencing unprecedented challenges of rapid urbanisation, strained and aging infrastructure, social unrest and the increasing impacts and concerns of climate change. The need for cities to adapt or die has never been greater.

The concept of Resilience has provided a possible solution to help deal with the above challenges, as well as with the unpredictable nature of the future, as it provides an approach to understanding and dealing with change that is different to traditional approaches. However, the context of the on-going debate on sustainability and resilience (urban resilience in particular) requires rethinking our current way of viewing the world and the consequences of our actions, not only for the immediate future but also in the years to come. Before the concept of resilience and how systems lose their resilience can be explored, it is important to understand and describe the system in its current and past states (Resilience Alliance, 2010, p. 5). Describing the urban system and how it changes forms the main focus of the study.

This chapter provides the point of departure for the study by introducing the background and rationale for the study, reviewing why we should look at urban resilience and urban change. This is followed by outlining the aims and objectives as well as the limitations and scope of the study. The chapter will conclude by outlining the structure and content of the dissertation.

1.2. Background and context to the study

This section will provide the overarching background and the context of the study. It will start by providing the context of the study by describing some of the challenges that cities will face in the future and that the concept of urban resilience can provide a solution to help manage the challenges. Through the discussion on resilience, the rationale and relevance for studying urban change will be made clear.

1.2.1. Context of the study

This study forms part of a larger research project, Resiliency Strategies for Aspirational African Cities (a project funded by the South African National Research Foundation (NRF) under the global change grand challenge research theme). The project's core focus is that of understanding resilience and mitigating climate change within urban and ecological systems. As the project sits within the University of Pretoria, the project's case study area is that of the City of Tshwane (formally Pretoria), see Figure 1 for a location map of the city.

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Figure 1: The location of the City of Tshwane Metropolitan Municipality within the context of South Africa (top left) and the Province of Gauteng

The project is currently in its first phase, which is to develop an understanding of the application of resilience theory in urban social-ecological systems (USES). In order to create the best possible understanding of the USESs the project team has chosen to conduct several case studies of areas within Tshwane. As this is a very large, multi-disciplinary and complex project, the first phase has been split into six different parts to be carried out in five Masters Studies, of which this study is one, and one PhD study.

This study is a result of the challenges that were faced, and how the need for this research was identified, while undertaking research to apply the Resilience Alliance's resilience (2010) assessment process on two neighbourhoods within the City of Tshwane. The Resilience Alliance (2010) assessment was originally developed for assessing the resilience of social-ecological systems; and a city can also be considered as such a system (Davoudi et al., 2012; du Plessis, 2011, 2009). Most of the emphasis of the assessment is placed on ecosystems or the effect that the social system has on the resilience of

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ecosystems (Porter and Davoudi in Davoudi et al. 2012, p. 331); see Nel et al. (2013, p. 4) for a critique of the assessment, with little focus on social aspects.

1.2.2. Resilience

Cities are currently experiencing many challenges, including climate change and extreme weather, civil unrest, terrorist attacks and economic instability. These uncertainties remind us of the unpredictable, and sometimes chaotic, nature of the world which we live. Resilience has been presented as a concept and approach to help to manage in these unpredictable times (Davoudi et al., 2012, p. 299). However, there is no clear consensus on what resilience means, other than the assumption that resilience is good. This assumption has been readily taken up by many governments and NGOs around the globe, who have hastily included resilience into polices as well as compiling generic resilience assessments (Davoudi et al., 2012, p. 299).

South Africa is no exception to this trend. Some examples of how South Africa has taken to resilience can be seen in (1) how resilience has been incorporated into national legislation, as resilience, or rather urban resilience, is now a key principle of the newly promulgated Spatial Planning and Land-Use Management Act, Act No. 16 of 2013 (Republic of South Africa, 2013). (2) Resilience has also been widely used by the South African Cities Network (SACN), a non-profit research organisation, in their State of the Cities Report (South African Cities Network, 2011) and a report on the Analysis of Cities Resilience to Climate (South African Cities Network, 2014). (3) Lastly by the City of Tshwane (the capital city of South Africa and formally known as Pretoria), has incorporated resilience as a key component of the Tshwane 2055 Vision for the City (City of Tshwane, 2013). In all three of these examples resilience has been used very loosely and with very little understanding and description of what it is, how to assess it and how resilience can be achieved.

Although the aim of this study is not to conduct an urban resilience assessment, the concept of resilience, is nonetheless, important for this study. Resilience can be defined as the ability of a system (such as a city) to withstand sudden shocks, like floods, while at the same time having the capacity to adapt to, learn from and anticipate long-term incremental, changes, like climate change, without changing its basic state (Ahern, 2011; Alberti and Marzluff, 2004; Folke et al., 2004; Gotts, 2007; Resilience Alliance, 2010; Roggema, 2012; Walker et al., 2004). Resilience provides a means not only to recover from a shock but also to adapt to and anticipate possible future shocks.

Resilience, as we know it, has its origins in environmental sciences, particularly in the study of social-ecological systems (SES) (Davoudi et al., 2012; Gunderson and Holling, 2001). Social-ecological systems (SES) refer to a "tightly coupled dynamic relationships in which humans, their social structures and their biophysical environment interact with each other as parts of one interdependent system"(du Plessis, 2008a, p. 15). These systems impact on, and are influenced by, the natural environment in which they exist (Coelho and Ruth, 2006; du Plessis, 2008a, 2008b; Grimm et al., 2000). Social-ecological systems should not be seen as "social systems plus ecological systems" (Norberg and Cumming, 2008, p. 278). Instead, they are integrated systems and should not be viewed as separate

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entities, as one (sub)system impacts on the other in different ways and at different spatial and temporal scales (Folke, 2006; Gunderson and Holling, 2001; Norberg and Cumming, 2008).

Considering the current trend and use of resilience in South Africa, it is not inconceivable that practitioners, such as urban planners, may be asked in the near future to conduct urban resilience assessments as part of an environmental impact assessment (EIA), a township establishment application, or as part of a spatial development framework (SDF). The resources available to such practitioners are tools like the resilience assessment workbook developed by the Resilience Alliance (2010).

The Resilience Alliance, one of the world's leading research groups on resilience of SES, has developed a workbook, as guidance for practitioners in assessing the resilience of SES (Resilience Alliance, 2010). The workbook outlines a methodology (shown in Figure 2) to assess the resilience of SES. Some of the key components and critiques of the methodology will be highlighted below.

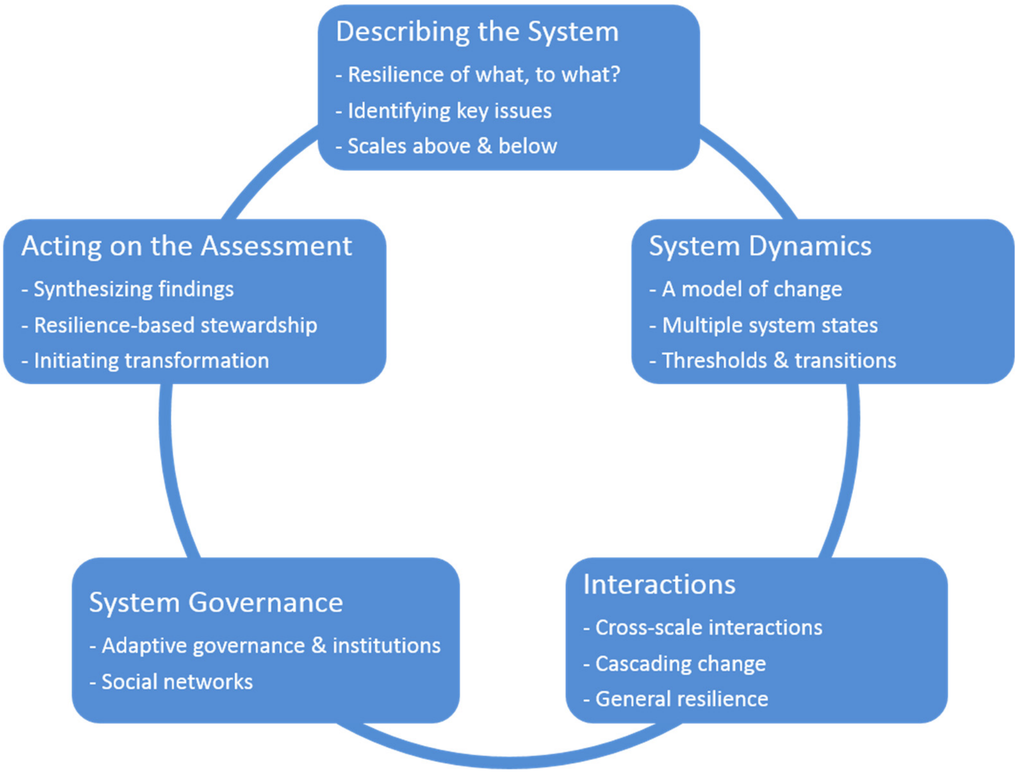

Figure 2: Resilience Alliance's Resilience assessment framework (Resilience Alliance, 2010, p. 5)

The Resilience Alliance (2010, p. 10) argues that, in order to do a resilience assessment, it is first important to describe the focal system (the part of the system that is being observed). And in order to describe the focal system one must place soft boundaries around the system[3]. However, they do not provide adequate guidance of how this should be done. Similarly, when reviewing similar studies on resilience (see Alberti and Marzluff (2004), Davoudi et al. (2012), Folke (2006), Folke et al. (2004),

[3]The importance and need to place boundaries when studying systems has also been argued by Alexander (1999), Cilliers (2008), Cumming et al. (2005), Walker et al. (2002), to name but a few. This point will be discussed in more detail in Chapter Four

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Gunderson and Holling (2001) and Kinzig et al (2006)) there is a lack of guidance, methodology or framework for how to describe the system that is being observed. What would be important to consider and what not?

This guidance is given without first describing how to identify what the system may consist of. Secondly, there is an underlying assumption that there is an issue within the system that is under observation, for the Resilience Alliance a "useful place to start [to set the system boundaries] is therefore to define the issues that the assessment will seek to address" (Resilience Alliance, 2010, p. 10). What if, hypothetically, the system that is being studied has no apparent 'issues'? This means we cannot simply answer the question that the Resilience Alliance poses of "RESILIENCE OF WHAT" (Resilience Alliance, 2010, p. 11). This issue-based approach that the assessment uses (Resilience Alliance, 2010, p. 10) creates somewhat of a conundrum of how one should be studying systems.

The best guidance given by the Resilience Alliance on how to describe the current state of the focal system (and, through it, to describe the system), is that:

> "any system can be described by a small number (usually 3-5) of key variables that characterize and determine its current state. The conditions of these key variables and the nature of their relationships are equally important considerations for defining the state of the system"(Resilience Alliance, 2010, p. 25).

Again this description does not provide many clues on how to describe a system. The task of describing a system becomes harder when this thinking is applied to the urban system, with its many intricacies, in an attempt to assess the general resilience of a particular urban area.

Walker et al. (2002) echo much of what the Resilience Alliance (2010) outlined, but provide some small guidance in the form of their own framework for analysing social-ecological resilience. Within their framework, they ask a series of questions that they use to help describe the system and the changes of the system they are studying. The questions they ask are:

- "What are the spatial boundaries of the SES?"
- "Who are the stakeholders?"
- "What are the key components of the SES, what are their turnover times, and to what extent are their dynamics endogenous vs. influenced by exchange across the boundaries of the SES?"
- "What is the historical profile of the system? How did it get to be what it is now—what changes occurred through its history in terms of ecosystem, technology, society, economy, and so forth?" (Walker et al., 2002, p. 7).

However, Walker et al. (2002), like the Resilience Alliance (2010), do not provide sufficient guidance on how these questions can or should be answered. This lack of guidance is further compounded when asking how this can be applied to the urban system.

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1.2.3. Urban change

As the discussion above has indicated, one of the key components of assessing the resilience of any SES is the ability to describe the system. A second important part of a resilience assessment is to be able to describe how the system has changed over time (Resilience Alliance, 2010; Walker et al., 2002). An assessment of the changes that the system has undergone is done because no SES is static. Rather, they are in a constant state of flux. With periods of growth, stability and rapid change (Gunderson and Holling, 2001; Holland, 2012; Johnson, 2002). The rate of change of the system can depend on the scale of the focal system, how it interacts with the systems on higher and lower scales, as well as its internal dynamics.

The question, though, is 'why look at change?' The Resilience Alliance (2010, p. 22) provides an answer for this by saying that:

> "Change is always occurring, and if we ignore it or attempt to prevent it rigidly, we may miss opportunities or create new challenges to achieving long-term sustainability. Social-ecological systems can experience both gradual and rapid changes. Managing for resilience requires understanding cycles of change and the vulnerabilities and windows of opportunity that these cycles of change introduce to your system"

In other words, we cannot prevent change from happening, nor should we, as new opportunities come with change that can be exploited to help achieve our goals. Additionally, to reach our goals, be they sustainability or resilience, understanding and managing change is vital.

Urban planning is often seen as the management of change (de Roo et al., 2012; Innes and Booher, 2010; Rondinelli, 1973) and, as the concept of resilience becomes ever more popular within the urban planning community, the need to understand resilience and its implications is becoming more important. However, if resilience is to be understood and used within the urban planning field, it first requires that a step be taken back and the theoretical principles/foundations on which resilience theory has been built be understood. And, to understand the theoretical underpinnings of resilience theory, an understanding of the approach to resilience should first be understood.

Elmqvist et al. (2004), Folke (2006), Gunderson and Holling (2001), Norberg and Cumming (2008), Ostrom (2007), Resilience Alliance (2010) and Walker et al. (2002), to name but a few, all agree that a complex adaptive systems' (CAS) approach should be used when studying SES and resilience. Furthermore, du Plessis (2008b) argues that a SES, and by extension CAS, approach should be used when approaching the study of cities and urban resilience. This is, as argued by du Plessis (2009, 2008a, 2008b), Evans (2011) and Roggema (2012), because cities are complex adaptive systems, as well as social-ecological systems. Furthermore resilience is as an emergent property of a complex adaptive system (Folke, 2006; Roggema, 2012). As a result, the argument is that both SES and cities display the properties that distinguish complex adaptive systems from any other type of system (Gunderson and Holling, 2002; Holland, 1996; Johnson, 2002; Taylor, 2005). Thus, to understand resilience and how

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to make cities resilient, the first point of departure should be understanding complex adaptive systems.

Complex adaptive systems (CAS) are non-linear, self-organising networks made up of many diverse elements whose interactions both define the system and enable new patterns to emerge that are more than merely the sum of the individual parts. Furthermore, CAS adapt to changes in their environment (Cilliers, 1998; Holland, 2012). Complexity theory seeks to provide a means to understand the inherently complex behaviours of CAS by understanding how these systems manifest in time and space, as well as why we see particular types of behaviour from these systems (Cilliers, 1998; Geyer and Rihani, 2010; Holland, 2012, 1998). Although each system is unique there are several recurring patterns, processes and properties that are common to all CAS. These will be explored within the study, as well as the applicability to the urban setting.

1.3. Research objective

Although the assessment by the Resilience Alliance (2010) has flaws, it does provide a useful, and among the very few, assessment procedures that one can follow to assess the resilience of a system. Furthermore, as the majority of the work on resilience and SES have had a focus on ecological systems and not urban system, there are very few tools available for studying urban social-ecological systems. For this reason, this study will seek to provide some tools for the application of SES theory to the urban context. The objective of this dissertation is not to assess the resilience of any particular system. Rather, it aims to address some of the shortcomings of the existing frameworks that have been discussed above. It aims to do this by providing a 'plug-in' that can supplement the existing frameworks.

If urban planners aim to achieve resilient cities, and if resilience assessments are to be done in the future, there is an urgent need to ensure that these assessments are based on sound theory, are user friendly, clear and understandable. In order to address the challenges discussed above, this study aims to achieve four main objectives:

The first objective of this study is to provide a theoretical point of departure that will serve as the theoretical basis for the study and from which the other objectives will build on. The first object is:

Objective 1: To identify a theoretical basis that can describe the behaviour, structure and changes of cities.

As the Resilience Alliance (2010) and Walker et al. (2002) describe, an important factor for assessing resilience is the ability to describe the system that is being studied. As the majority of the tools available have been developed for ecological studies this study will seek to provide a tool for the urban context. For this reason, the second objective of this study is:

Objective 2: To develop a framework for describing an urban system.

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Resilience theory emphasises understanding how a system changes (Gunderson and Holling, 2001). Consequently, any study that seeks to examine the resilience of a system will require a longitudinal study of the system and how it has changed. This is because social-ecological systems undergo change over time (Resilience Alliance, 2010). And that by "Understanding what is behind these changes—the change drivers—can provide insight into how historical system dynamics have shaped the current focal system and what effects they might have in the future. A historical profile of the system can also reveal changes in system resilience over time"(Resilience Alliance, 2010, p. 18). In order to achieve this the third objective for this study is to:

Objective 3: Translate resilience theory constructs for mapping change into the urban context.

The fourth objective seeks to demonstrate how the theoretical constructs described throughout this study can be applied to the urban context.

Objective 4: To illustrate the application of the concepts to the urban environment.

1.4. Scope and limitations

This is an explorative study into the field of urban change. This study does not seek to provide or create a resilience assessment or methodology, as existing assessments are already available, nor does this study seek to assess the resilience of a system. Rather, it seeks to provide a necessary component or input into existing resilience assessments (see Figure 3 for this studies fit with the Resilience Alliance's framework) , such as the one created by the Resilience Alliance (2010), in order for the users of these assessments to better understand the system that they are studying so as to be able to apply the chosen assessment. Furthermore, this study forms part of a larger research project and as a result, it

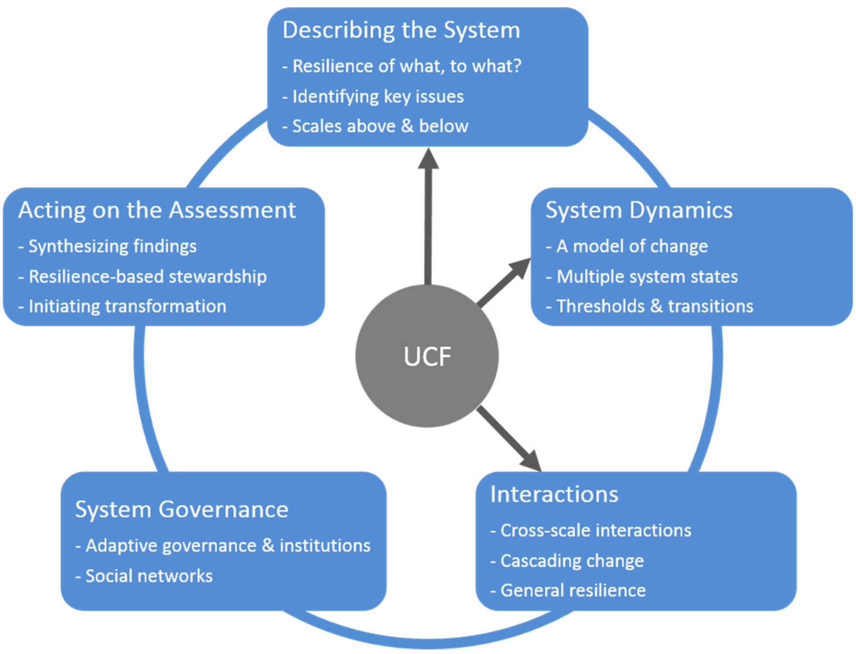

Figure 3: Urban Change Frameworks (UCF) provides input into the Resilience Alliance's framework at three key places

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has a very specific focus. Other aspects of resilience (social, economic and environmental) are being studied by other members of the research team.

A mixed methodology approach has been used within this dissertation. This has been done by combining a conceptual (non-empirical) research design as well as an applied methodological study research design. In using this methodology, theoretical concepts and ideas are seen as the data to be collected and analysed to build new theory or, as is the case for this study, a methodological framework.

The various parts of the methodological framework presented within this dissertation have been illustrated and tested by using existing case studies. As the case studies are used primarily for illustrative purposes the methodology used to collect the data within the case studies will not be discussed (see Nel (2011, p. 11) for the methodology used for the case studies). Additionally, the case studies that were used were based on a dissertation by Nel (2011), which focused on identifying the drivers of spatial change. As a result of the use of secondary data, there are two main limitations to the data. The first being that not all the data from the case studies was applicable to this study. Secondly because of Nel's (2011) specific focus on spatial change, there are aspects of the framework that could not be fully tested.

This study draws heavily on the Resilience Alliance (2010) workbook for the assessment of the resilience of SES, as this dissertation seeks to fit into the gaps that have been identified in the above discussion.

The underlying theoretical assumptions on which this study is based are that cities are complex adaptive systems (Batty, 2007; Innes and Booher, 2010; Nel, 2009). Secondly that social-ecological systems are also complex adaptive systems (see Elmqvist et al. (2004), Folke (2006), Gunderson and Holling (2001), Norberg and Cumming (2008), Ostrom (2007), Resilience Alliance (2010) and Walker et al. (2002)), and for this reason cities are complex adaptive systems as well as social-ecological systems (Davoudi et al., 2012; du Plessis, 2009, 2008a, 2008b; Evans, 2011; Roggema, 2012). Furthermore, as all complex adaptive system exhibit the same characteristics (Cilliers, 1998; Holland, 1996), albeit in different ways, many of the concepts from one field of study, i.e. change in SES, can be applied to another, i.e. change in urban systems. These assumptions will be supported where possible throughout the text of the dissertation.

1.5. Structure of the study

The dissertation is made up of seven chapters and can be divided into five parts, as illustrated in Figure 4. The first part of the study containing this chapter, introduces the study by providing the background, research objectives and scope and limitations of the study. The second part of the study, Chapter 2, provides the theoretical body of the dissertation by (1) providing an overview of how the approach to studying the cities has changed, (2) reviewing systems and complexity theory and (3) how cities can

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be understood as complex adaptive systems. The third part, containing chapter 3, describes the research design and methodology of the dissertation.

The fourth part consists of Chapters 4, 5 and 6. It contains the methodological framework developed in this study and addresses the main objectives, mainly to describe the urban system and how it changes. Within this section, reference has been made to two case studies used as a means to test and illustrate the various parts of the framework. Chapter 4 contains three main sections. The first section presents the overarching argument and approach for the framework. The second discusses the importance of setting boundaries on a system as well as how various boundaries can be set on a system. The last section of Chapter 4 describes a methodological framework for describing the urban system at a particular point in time. This section looks not only at a general description of the urban system but also includes a spatial description of the urban system. Chapter 5 examines how changes in the system can be identified. Here cross-scale spatial and temporal interactions have been included in the identification of changes within the system. Chapter 6 makes up the last part of this section and describes how the changes identified in Chapter 5 can be described.

Chapter 7 concludes the study by discussing how this study has achieved its objectives, to provide a method to describe the urban system and how it changes. As this dissertation is an explorative study, recommendations on future research are made.

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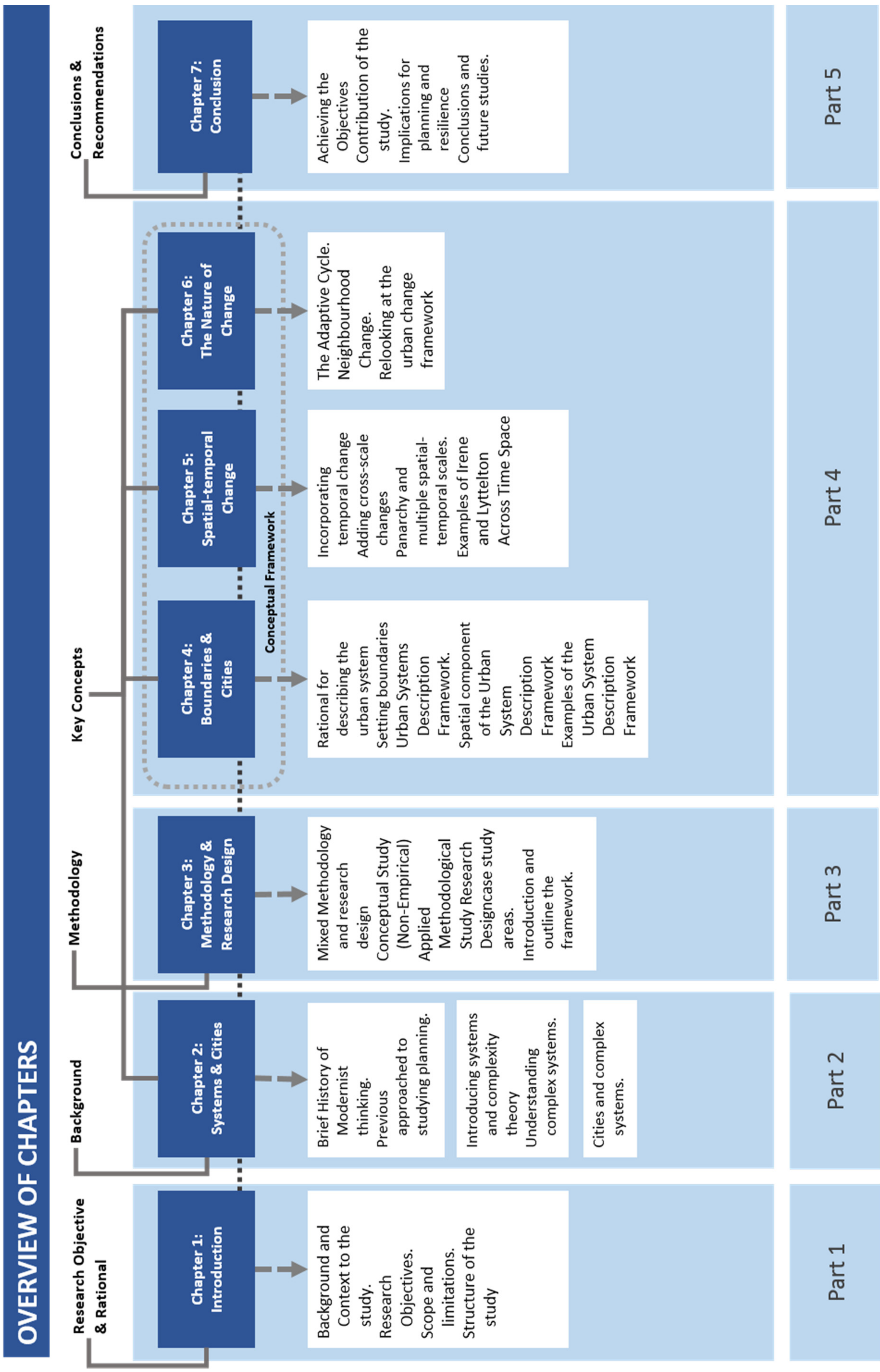

Figure 4: Overview and structure of the study

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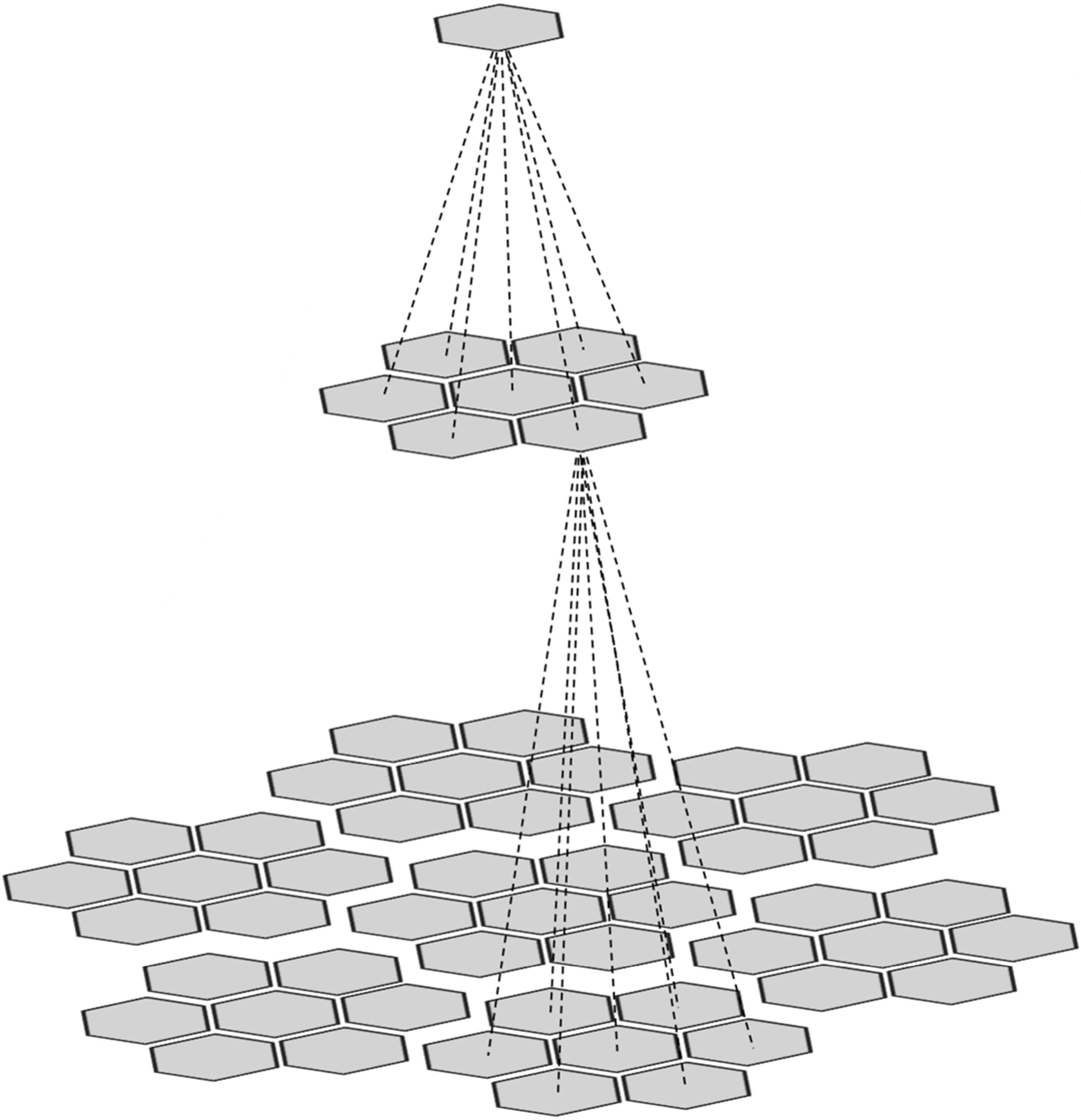
Chaper 2: Systems and cities



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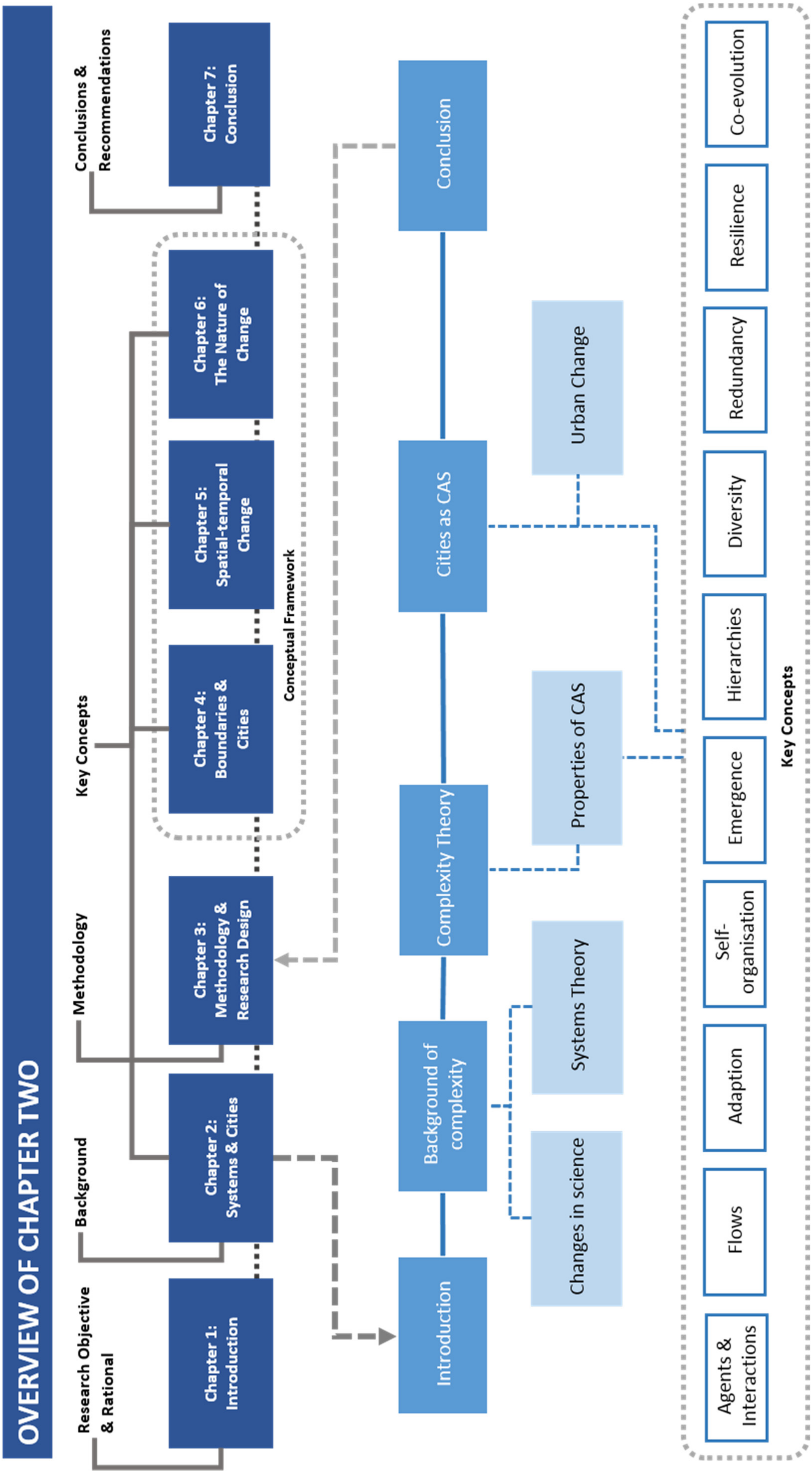

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2.1. Introduction

This chapter will serve as a basis for the broad theoretical discussion for this dissertation by focusing on complexity theory and its application to cities and how they change. The focus is not to explore the history of planning or design, as this topic has been well covered by many authors, see Birch (2009), Hall (2014, 2002, 1989), LeGates and Stout (2009), Madanipour (2007), Taylor (1999, 1998) and Ward (2004).

The chapter will start off with a brief history of how our approach to the science and study of cities has changed. It will argue that the past approaches to studying cities and urban change are insufficient, as they are based on modernist principles that see the city as a simple, static entity that can be understood by breaking it down into its basic parts. As will be shown, this is far from the truth. The argument will then be made that a systemic view of cities is required and that a complexity theory based approach is the best suited to this task. This will be done by providing a brief history of complex systems' science after which an in-depth discussion of complex systems, their properties and applications of the theory to cities will be provided.

2.2. From order, chaos and complexity

Before we delve into the theory of complexity and systems, it may be useful to understand the long process that has led to the development of these concepts, as well as how our way of thinking and viewing the world has changed over many years. As will be shown, much of our thinking in the past has been influenced by philosophers and physicists, who then influenced the world views of the thinkers of their time. As a result, much of the focus of the initial discussion will be on physics and philosophical ideas, and how they have changed over time. This will be done by looking briefly at the theories and ideologies pre-systems theory (general systems theory 1950's) and then some of the theories and/or concepts developed in recent times.

2.2.1. A clockwork universe

This story begins in the Middle Ages where the dominant world view was characterised by a subordination of individual needs to the community, as well as an interdependence of material and spiritual phenomena. The scientific thinking of this time was held predominantly by the Church (Capra, 1984, p. 53). The nature of science during the medieval period was "based on both reason and faith and its main goal was to understand the meaning and significance of things, rather than prediction and control" (Capra, 1984, p. 53). The medieval approach questioned the meaning and purpose of natural phenomena in relation to God, the human soul and ethics (Capra, 1984, p. 54; Kauffman, 1995, p. 5).

During the sixteenth and seventeenth centuries this underwent a drastic change as the view of the organic, spiritual and living universe was replaced by the view of the world as a machine. This 'new' way of thinking was to be the foundation of the modern era and was brought about by a change in

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thinking in the fields of physics, astronomy and politics/sociology by Nicolas Copernicus, Galileo Galilee, René Descartes, Francis Bacon, Thomas Hobbs and Isaac Newton, to name but a few (Ball, 2005; Capra, 1984; Fleming, 1991; Kauffman, 1995; Peat, 2002). The scientific revolution of the sixteenth and seventeenth centuries started with Nicolas Copernicus who challenged the view that the earth was the centre of the universe with the notion that the earth was simply a planet orbiting a star, along with many others. This was taken further by Johannes Kepler who developed the laws of planetary motion (Capra, 1984, p. 54; Fleming, 1991, p. 414; Peat, 2002, p. 3).

The major change in scientific reasoning came from Galileo Galilee who, after discovering the law of falling bodies through observations of the heavenly bodies, was able to confirm, without any doubt, the Copernican hypothesis as a valid theory (Ball, 2005, p. 39; Capra, 1984, p. 54). Thanks to the work by Galileo, a new dominant scientific approach became the norm. This entailed the use of an empirical approach and mathematics to describe nature. Through mathematics one could show that nature was orderly and predictable. This has underlined a great deal of the scientific thinking up to the present day (Capra, 1984, p. 55).

Francis Bacon supported this new approach. By applying a new method of inquiry which involved the "mathematical description of nature and the analytic method of reasoning" (Capra, 1984, p. 55), which was first brought about by Descartes, Bacon cemented the scientific methodology of empirical experimentation, drawing conclusions followed by further experimentation. This also seeded the approach of modern science to measure and quantify nature. With this, the view of 'nature as machine' was set into the realm of science (Capra, 1984, p. 55; Coveney and Highfield, 1996, p. 19).

The next major breakthrough in scientific thought came from René Descartes, who advocated rationalism and developed an analytical method (analytic geometry), which he believed would allow him to reduce all physical phenomena to exact mathematical relationships (Capra, 1984, p. 59; Geyer and Rihani, 2010, p. 12; Madanipour, 2007, p. 149; Peat, 2002, p. 38). His method consisted of breaking up problems or things into pieces and arranging them into their logical order and then regrouping them (Madanipour, 2007, p. 149). This, Capra (1984, p. 59) argues, "has become an essential characteristic of modern scientific thought theories and the realisation of complex technological projects". The downfall of this Cartesian thinking (as it is also known) is that the overemphasis of this method of thinking has led to a division "that is characteristic of both our general thinking and our academic disciplines, and the widespread attitude of reductionism in science – the belief that all aspects of complex phenomena can be understood by reducing them to their constituent parts" (Capra, 1984, p. 59).

Descartes viewed the wold and the universe as nothing more than a machine (hence the saying 'a clockwork universe' or 'man as machine') that could be understood in terms of the movements and arrangements of its separate parts. In this way, the world can be seen as predictable (Ball, 2005, pp.

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40 – 41; Capra, 1984, p. 60; Gershenson, 2012, l[4]. 6243). Descartes' view of the universe extended to the living/biological realm and had a significant effect on the development of the life sciences (Madanipour, 2007, p. 3). This reductionist view considered living organisms simply as a collection of parts of a machine. This view was also extended to the city (Capra, 1984, p. 62; Gershenson, 2012, p. 6243; Madanipour, 2007, p. 149). Although the limitations of the Cartesian world view have come to light in most fields of scientific enquiry, the general method of approach to intellectual problems still remains valuable (Capra, 1984, p. 62).

Completion of the Cartesian world view was brought about by Isaac Newton in the seventeenth century. Newton synthesised the works of Copernicus and Kepler, Bacon, Galileo and Descartes and created a mathematical theory of the world, thus completing the mechanistic view of nature. The importance of his theory included the laws of nature and their universal application (Capra, 1984, p. 63; Fleming, 1991, p. 415; Kauffman, 1995, p. 6; Peat, 2002, p. 117). Pierre Simon de Laplace took this view even further arguing that, "if at one time, we knew the positions and motion of all the particles in the universe, then we could calculate their behaviour at any other time, in the past or future" (Geyer and Rihani, 2010, p. 13). The success of Newtonian mechanics was soon extended to other fields of enquiry, as it was generally believed that it could explain everything (Ball, 2005, p. 39). Examples of this can be seen in the motions of fluids, the vibrations of elastic bodies, and would later be used to explain the theory of heat (Ball, 2005, pp. 40 – 41; Capra, 1984, p. 67). The achievements of the industrial revolution of the eighteenth century was largely brought about as a result of the success of this world view, which then increased confidence in the approach (Geyer and Rihani, 2010, p. 13).

This Newtonian view can be summarised by four rules. The first being that of order; that every cause at any one time or place has a known effect(s). The second rule is that of reductionism: That the whole can be understood by dissecting and understanding the individual parts. The third rule is that everything can be predicted so, if one knows the global behaviour, one can predict the future of the behaviour by simply adding the appropriate variables into a model. The fourth and final rule is that of determinism, so that all things follow an orderly and predictable path (Geyer and Rihani, 2010, p. 13). In this view, the world was "less of a home in which to live than an object standing before us to be understood, described, predicted and controlled" (Peat, 2002, p. 118).

A notable attempt to use the concept of Newtonian physics in the social and political environment can be seen in the work of Thomas Hobbes' '*Leviathan*' (first published in 1651) in which Hobbes attempts to discover the universal laws that governed social and political life (Ball, 2005; Hobbes, 2003). An important aspect of Newton's theory is the predictability of everything (Ball, 2005, p. 41). As a result, Hobbes reasoned that, as Newtonian theory seeks to describe the motion of bodies, the same thought can be applied to people to predict social behaviour. He described two types of motion found in 'animals', the first being *Vitall* motion, as Hobbes names it, which "begun in generation, and continued without interruption through their whole life; such as are the *course* of the *Bloud*, the *pulse*, and the

[4] The notation l. has been used to refer to the Kindle Location. This notation has been used for citations where the source is an e-book and thus has no page number but rather a location within the text.

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Breathing….to which motions there need no help of Imagination" (Hobbes, 2003, p. 118). These are essentially the primal functions or motions that our bodies undertake in order to live and require little or no conscious thought. The second motion is *Voluntary* motion; which requires '*Imagination'* (consciousness) as it is the beginning of discretionary or unsolicited motion as well as thought and speech (Hobbes, 2003). Hobbs attempt to discover laws that govern society fell short as these rules are too rigid and mechanical (Ball, 2005). However, the concept outlined by Hobbes does provide interesting food for thought.

2.2.2. The 2nd law

Throughout the nineteenth century, the Newtonian 'world as machine' model became increasingly more complex and elaborate as it spread to various fields of study. However, new discoveries and ways of thinking began to identify the limitations of the mechanistic model of the universe, that not all things were orderly and predictable (Geyer and Rihani, 2010, p. 15). This inevitably opened the way for new discoveries and ways of thinking.

Among the most profound ways of thinking that emerged to challenge the Newtonian approach in the nineteenth century were the concepts of evolution, change, growth and development. From these concepts, Darwin's theory of Evolution and the science of thermodynamics are perhaps the most well-known (Ball, 2005; Capra, 1984; Geyer and Rihani, 2010; Kauffman, 1995).

Darwin's theory was based on the concepts of "chance variation – now known as random mutation – and natural selection, which were to remain the cornerstones of modern evolutionary thought" (Capra, 1984, p. 72). By accepting the notion of evolution, scientists were forced to abandon the Cartesian concept of the world as machine and to see the universe as a constantly changing and evolving system instead, where simple forms lead to complex structures. In biological evolutionary theory, this new way of thinking led to the belief that evolution meant a movement towards increasing complexity and order (Fleming, 1991, p. 419; Kauffman, 1995, p. 7; Peat, 2002, p. 143). The opposite was believed to be true in physics, where evolution meant a movement to an increase in disorder. From the latter, the field of thermodynamics was born and thus the science of complexity (Capra, 1984, p. 72).

"Thermodynamics is the science of change – and without change there is nothing to be said" (Ball, 2005, p. 44). Thermodynamics is based on some fundamental laws. The first being the conservation of energy; which states that energy can never be destroyed but rather converted into an alternative form (Ball, 2005, p. 44; Capra, 1984, p. 72). The second law of thermodynamics is related to the dissipation of energy. The second law states that "While the total energy involved in a process is always constant, the amount of useful energy is diminishing, dissipating into heat, friction and so on" (Capra, 1984, p. 72). The value of the second law is that it brings into focus the concept of time and the fact that time is irreversible and moves ever forward and never back (Ball, 2005, p. 45; Capra, 1984, p. 73; Coveney and Highfield, 1996, p. 152; Gleick, 1998, p. 257). The second factor that the second law brings into focus is that in an *isolated* system, the system will always move to a state of

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disorder (*Entropy*). An increase in entropy marks the progress of time, something that could not be explained through the Newtonian theory (Ball, 2005, p. 45; Capra, 1984, p. 73; Coveney and Highfield, 1996, p. 152; Gleick, 1998, p. 257; Sardar et al., 1999, p. 72). That is until the introduction of probability theory (statistical probability), which showed that the second law of thermodynamics was statistically sound.

Probability theory, unlike Newtonian mechanics, did not seek to know the movement of every particle but rather their average behaviour. Initially developed to understand the relationship between pressure, temperature and volume of gasses (Boyle's law of partial pressures), this discovery also led to the creation of the internal combustion engine that shaped the world in which we live. The phenomenon of statistical probability can also be applied to the swarming of bees, as well as a range of other natural phenomenon (Ball, 2005, pp. 46 – 57; Capra, 1984, pp. 73 – 74). The introduction of statistical probability into physics in the nineteenth century soon crossed over into other disciplines. Among them, the social sciences where statistics were being used to work out, for example, the population growth and probable life-expectancy of the population, which are crucial to know if one is to govern a country effectively (Ball, 2005, pp. 61 – 85).

2.2.3. $E= mc^2$

At the end of the nineteenth century, the Newtonian world view had been displaced from its pedestal as the primary way to describe natural phenomena. Theories such as evolution, for example, showed that the world was far more complex than Descartes and Newton had previously thought (Capra, 1984, p. 75). The introduction of the special theory of relativity and later the quantum theory or quantum mechanics by Albert Einstein (together with a group of scientists) brought a new way of looking at natural phenomena (Capra, 1984, p. 75; Coveney and Highfield, 1996, p. 79; Kauffman, 1995, p. 23).

> "Every time they [the scientists] asked nature a question in an experiment, nature answered with a paradox, and the more they tried to clarify the situation, the sharper the paradoxes became…scientists became painfully aware that their basic concepts, their language, and their whole way of thinking were inadequate….It took these physicists a long time to accept the fact the paradoxes…are an essential aspect of atomic physics..[and]…that they arise whenever one tries to describe atomic phenomena in terms of classical [Newtonian] concepts" (Capra, 1984, p. 76).

Once scientists realised this, they began to ask the right questions to avoid contradictions. This new view of the world, in contrast to the Newtonian world view, can be characterised by concepts such as ecological, organic and holistic, to the point that this might be seen as a systems view in the sense of general systems' theory [discussed later]. The world was "no longer seen as a machine, made up of a multitude of objects, but has to be pictured as one indivisible, dynamic whole whose parts are essentially interrelated and can be understood only as patterns of a cosmic process" (Capra, 1984, p. 78).

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Among the paradoxes that became apparent to physicists was that sub-atomic particles displayed properties of both 'particles' and 'waves' at any one point in time. Realising this dual nature of matter, physicists began to look for the likelihood or probability and patterns that matter would exhibit any one of these properties. These patterns did not represent the probabilities of things, but rather the probability of the interconnections between things (Capra, 1984, p. 80; Coveney and Highfield, 1996, p. 80; Kauffman, 1995, p. 23). This meant particles could be understood, not as isolated objects, but rather only "as interconnections, or correlations, between various processes of observation and measurement" (Capra, 1984, p. 80).

This view of physics has had a breakthrough in how we look at the world. By focusing on the relationships between two particles or things, we can observe and understand more of the world around us, and to recognize that changes in one aspect can create unpredictable changes in another.

2.2.4. Reflection on past world views

Studying history and understanding how the past affects us is vitally important as we seek to move into the future. As the limitations of Descartes' and Newton's reductionist world views have become evident (many parts are still valid and form the basis of our understanding of the world), these world views still filter through to how we conduct our scientific inquiry. What modern physics has shown is that "we cannot decompose the world into independently existing small units...[but rather]…as a complicated web of relations between the various parts of a unified whole" (Capra, 1984, p. 81). It is this thinking that will be the focus of the rest of this chapter and study.

2.3. Systems: More than the sum of their parts

The previous section has shown that we have come a long way in our attempts to understand how the world around us works. We have moved from the reductionist, Newtonian, world view to a more holistic understanding of the universe as a complex system with countless interrelationships between objects. It is clear from the discussion above that the modernist view falls short and that it cannot be used to understand complex phenomena. Instead, to understand complex phenomena like urban change, we need to look at the interactions between the components and how these work to create the phenomena under scrutiny.

In order to provide a context, this section will first give a brief background to systems theory and some of its derivatives. However, the focus will be on complexity theory with particular reference to the notion of *Complex Adaptive Systems* (CAS), as this will be the primary approach used in this study. Before the various approaches are explored, some definitions and concepts will be provided to provide a common understanding of the terminology used throughout the remainder of this study.

2.3.1. Definitions and concepts

A common understanding of the language and concepts behind systems thinking is imperative as these are the fundamental building blocks of what is still to come. A few basic definitions and some

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terminology[5] that will be used in relation to complex systems are described below. Some of the concepts will be explored and expanded upon in more detail further on in the study.

To establish a sound foundation, a generic or base definition of a system will be constructed. This definition will be compatible with the various approaches to systems to be considered later. For the purpose of this study, a system is defined as:

> Being comprised of multiple agents that interact with each other, over a network, to produce a particular outcome, pattern or behaviour, through feedback mechanisms, that is more than the sum of the individual agents (Beinhocker, 2006; Capra, 1984; Cilliers, 2000; Meadows, 2008; Page, 2011; Richardson, 2005).

Important aspects to be noted in the definition of a system are when we talk about systems, we are referring to the *interaction*, two-way communication, between two or more *agents* (an agent, for example, can be a person). It is the “connections between the parts which make it a system” (Chadwick, 1971, p. 36). A connection between the agents must be achieved; otherwise no interaction can take place. For a connection to form, subsequently allowing for interaction between agents, information between these agents must be transmitted. In human systems, for example, this is done by talking (i.e. having a conversation), writing (i.e. email) or even through body language (Meadows, 2008, pp. 12–13). The final aspect to note is that the resulting interactions between the agents produce something that is more than what the two agents combined would be able to produce individually (Richardson, 2005a, p. 619). An example of this would be how small subsistence farmers produce a limited amount of produce when compared to a co-operative that produces more than all the subsistence farmers combined, while working on the equivalent size of land.

From this we can say that systems consist of:

- Agents
- Interactions or interconnections
- Networks or connections; and
- Interactions that produce something that is more than the sum of individual parts combined

Having discussed the basic terminology, it is now possible to ask ‘why should we look at different approaches to systems’? Richardson (2004a) argues because of the complementary law in systems; which “suggests that any two different perspectives (or models) about a system will reveal truths regarding that system that are neither entirely independent nor entirely compatible” (Richardson, 2004a, p. 76); it is useful to take note of different perspectives. By viewing alternative perspectives on a system, depending on the approach, we may find different answers that may or may not be compatible with an alternative perspective.

[5] A note on the terminology: Systems Theory refers to the general theory of systems (or General Systems Theory [GST]), to be discussed in the next section, while a system refers to the interaction of various entities with one another.

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If we are to take the complementary law of systems into consideration, we cannot ignore the fact that there are various approaches to systems, nor that each of these approaches will divulge their own truths about the system that we are observing. The following sections briefly look at General Systems Theory and how it has changed, after which a more detailed description of complexity theory, focusing on complex adaptive systems, will be explored.

2.3.2. Systems theory

The systemic view of thinking can trace its origins to the advent of thermodynamics in the 1800's (Capra, 1984, p. 72; Richardson, 2004a, p. 75). However, the current concept of systems began in the 1920's with Ludwig von Bertalanffy, a theoretical biologist, who developed open systems theory (Abraham, 2011, p. 382; Robert, 1999, p. 29). Although open systems theory was originally developed for use in biology, it soon spread to various fields of study, i.e. psychology. Von Bertalanffy later generalised his open systems theory for application in other fields of study. When he did this, he renamed it General Systems Theory, as he hoped it would be a general theory that would unite different disciplines (Robert, 1999, p. 31).

Systems theory, as we know it today, truly took off only in the 1950's when von Bertalanffy published, '*An Outline of General System Theory'* (von Bertalanffy, 1950) and a few years later (in 1956), Kenneth Boulding published '*General systems theory: The skeleton of science'* (Boulding, 2004). These publications, which described the general approach to and principles of systems in general, would help form the foundation of many governmental policies, as well urban planning theory and practice in the 1960's and 1970's (Abraham, 2011; Cantanese and Steiss, 1970; Chadwick, 1971; Laszlo and Krippner, 1998; Reif, 1973; Richardson and Midgley, 2007).
By the 1960's, systems theory had become much more diverse as many offshoots of the theory started to develop (See Figure 5 for an example of the different fields of enquiry that have developed around systems theory). Ironically, this is the opposite of what von Bertalanffy and Boulding originally conceptualised when they developed general systems theory, which was to be a unifying, multidisciplinary approach and not a field with any particular specialisations. Among the fields of study that emerged from general systems theory were systems' dynamics, complexity theory, viable system modelling, soft systems methodology, systems engineering and critical systems thinking.

General Systems Theory introduced a new holistic world view to the scientific community. This "holistic approach, which, in its most radical form, argued that everything affects everything else, and that any given phenomenon, such as unemployment, cannot be studied without looking at the entire context in which it is embedded" (Phelan, 2001, p. 132). Another part of the general systems theory concept is that simple changes or effects need not have a simple cause-effect relationship but can be, and often are, a result of complex non-linear interactions (Edson, 2008, p. 5; Phelan, 2001, p. 132). For Edson (2008, p. 5) systems thinking is "both a world view and a process; it can be used for both the development and understanding of a system and for the approached used to solve a problem". Senge (2006, pp. 68–69) describes systems thinking, as "a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than

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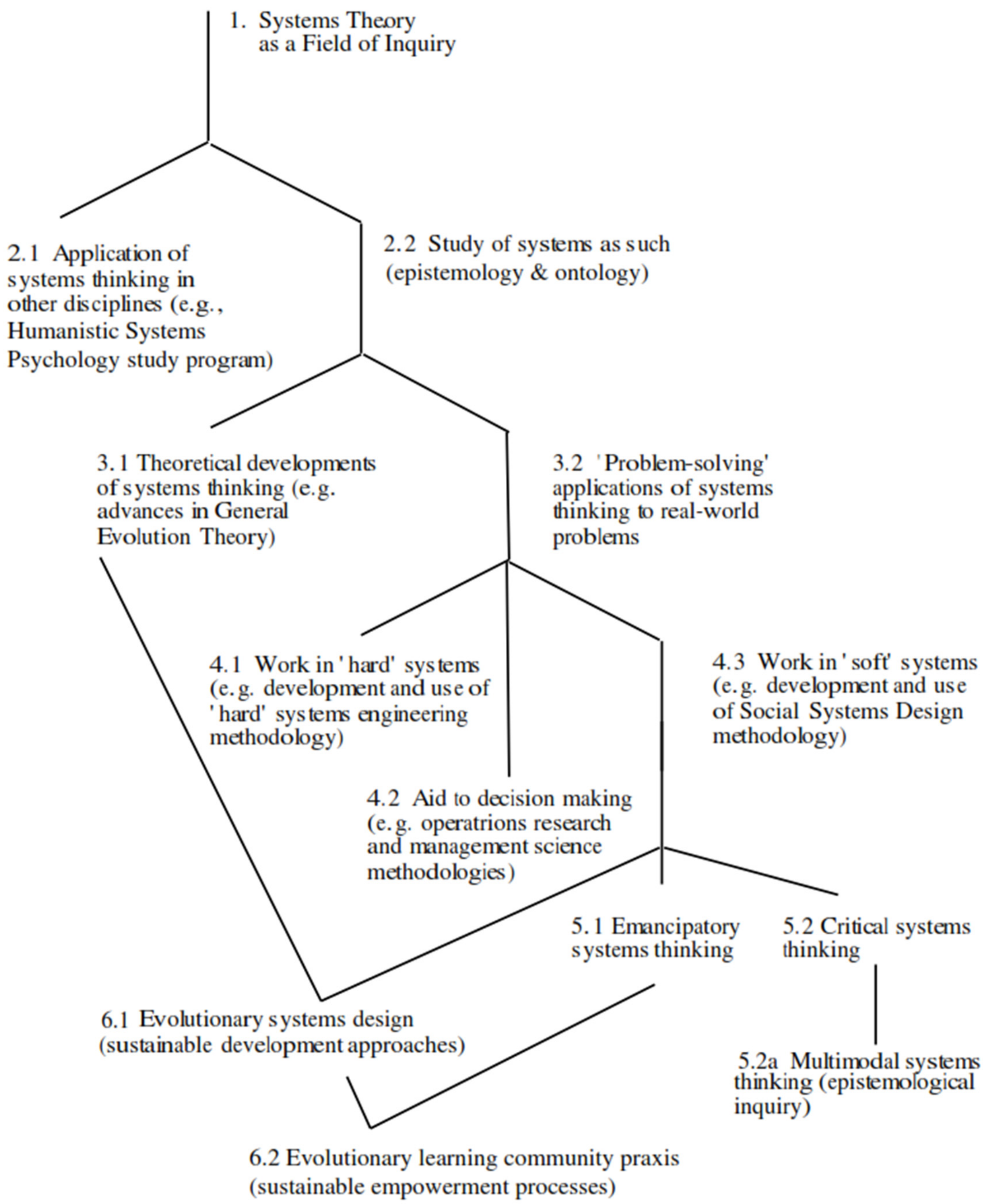

Figure 5: The shape of the systems movement, indicating the progressive development of particular theoretical branches (Laszlo and Krippner, 1998, p. 35).

static 'snapshots'". What Senge (2006) and Edson (2008) both argue is that a systems thinking world view is about seeing the 'big picture', the whole painting, instead of the individual brush strokes. The basis of the systems thinking approach is; instead of breaking down a system into the individual building blocks, trying to understand each block, then putting all the blocks back together to remake the whole (as a Newtonian approach would suggest); we should consider the world in terms of relationships and the integration of these relationships between the various agents (blocks) in the system.

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It is through these relationships that a system is greater than the sum of the individual parts (Ball, 2005; Beinhocker, 2006; Holland, 1996; Innes and Booher, 2010; Mainzer, 1997; Meadows, 2008; Page, 2011; Senge, 2006). Table 1 below offers summaries of how the systems view differs from that of the 'traditional' view. The main thing to note is that a systems view of the world looks at the whole and the relationships of the parts with each other, instead of the mechanistic 'deconstructionist' view that is consistent with the modernist view.

Table 1: Summary of the traditional view of the world compared to a systems perspective as described by Holbrook (2003, p. 77)

Traditional view	Systems View
Parts	Whole
Mechanistic	Organismic
Atomistic	Holistic
Reductionist	Ecological
Substance/matter/quantity	Form/ pattern/ quality
Classical	Romantic
Galileo/ Descartes/ Newton	Blake / Goethe / Kant
Analytic / dissection	Contextual / integration
Homeostasis	Self-organisation
Individual properties	Emergent properties
Hierarchies	Networks
Clockwork or watchmaker	The web of life or Gaia hypothesis
Classical physics	Quantum mechanics
Elementary components	Relationships or connections
Traditional psychology	Gestalt psychology

In addition to the discussion above, systems theory can be described through a few key aspects. These aspects of systems theory have been highlighted by Skyttner (2005, pp. 53–54) and are summarised in Table 2 below.

Table 2: Summary of the key aspects of Systems Theory as described by Skyttner (2005, pp. 53–54)

Aspect of Systems Theory	Description
Interrelationship and interdependence of objects	Only related and interdependent objects and their attributes can constitute a system
Holism	Holistic properties of a system that are not possible to detect via any analysis should then be capable of being defined within the system
Goal seeking	Interactions within the system must achieve a goal, approach equilibrium or final state
Transformation process	Inputs must be transformed into outputs in order to achieve the systems goals.
Inputs and outputs	In a closed system inputs are finite and defined from the beginning, whereas in open systems the additional inputs are taken from the system environment.
Entropy	Entropy refers to the movement to and/ or amount the amount of disorder or chaos present within the system. All systems move towards entropy unless new energy is added to the system
Regulation	In order for the system to attain its goals the interactions within the system must be regulated. Feedback is the primary way that the system regulates itself and maintains a stable state.

Aspect of Systems Theory	Description
Hierarchy	Hierarchy implies that systems are systems within larger systems. The nesting of these system is called hierarchy.
Differentiation	Some agents perform different or specialised functions. In this way labour within the system is divided.
Equifinality and multifinality	Systems may or may not achieve the same objectives in the same way given the same initial/ starting conditions. They many also arrive at a completely different goal given the same starting conditions.

The concepts self-organisation, emergence and adaption should be included in the concept of systems theory (Meadows, 2008; Phelan, 1999; Richardson, 2004a; Skyttner, 2005). However, these three concepts will be discussed in detail later in the chapter.

2.3.3. Critique of systems theory

Although systems theory is a useful tool for understanding the world around us, it has also received some criticism, particularly within the urban planning environment. Most of the criticism against using systems' thinking in urban planning was that systems' theory was used as part of rational planning theory/ approach to urban planning (Batty and Marshall, 2012, l. 685; Richardson and Midgley, 2007, p. 164; Taylor, 1998, p. 60) which was popular in the 1960's and 1970's (Richardson and Midgley, 2007, p. 164) and strongly advocated by authors such as McLoughlin (1970), Chadwick (1971), Reif (1973) and Catanese and Steiss (1970), to name but a few.

Among the critiques of systems theory was that it was deterministic in nature (Rotmans et al., 2012, l. 3991); was used to impose a top-down authoritarian way of thinking (Skyttner, 2005, p. 498); and that, according to Ryan (2007, p. 63), "Systems analysts assembled cookbooks of mechanical solutions to classes of recurring problems, rather than developing techniques that addressed emergent properties, interdependencies and environment influences".

Phelan (2001) maintains that, where complexity theory [to be discussed later] seeks to understand the rules that govern the system and lead to regularities, such as emergence, in contrast "systems theory almost seems to surrender to complexity because it is not particularly interested in the identification of regularities. Regularities do not exist in open systems, almost by definition" (Phelan, 2001, p. 132). Phelan (2001, p. 132) continues by saying that systems theory additionally limits itself through the study of bounded systems, instead of open systems.

With regard to systems' thinking in planning, there have been many critiques, including the fact that the use of systems' thinking in planning was focused primarily on models and techniques (Batty and Marshall, 2012, l. 684). Furthermore, many of these models were very large and difficult to apply as they were created in a laboratory setting which treated cities as machines rather than inherently complex entities (Batty and Marshall, 2012, l. 731). This view is echoed by Taylor (1998, p. 78), saying that "systems theorists wrote of 'modelling the urban system' and intervening to 'optimise it[s] functioning', as if the city were some kind of machine that had one politically uncontentious optimal state".

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Other critiques of systems theory in planning also included criticism for being too focused on control (Taylor, 1998, p. 60) and the focus being on the planner as the 'expert' or 'specialist' (Batty and Marshall, 2012, l. 745; Hall, 2002, p. 231; Taylor, 1998, p. 78) as if the adoption of this view "could lead to the identification and solution of urban problems independent of considerations of values or political debate" (Taylor, 1998, p. 78). This was seen as an excess of technocracy. Manson (2001, p. 406) comments that "During the rise of general systems theory, some geographers found it potentially useful as a means of modelling environmental systems…Others, however considered it irrelevant to social concerns, and in general, geographers have abandoned systems theory". In short, systems theory was critiqued as being too focused on building models, often without any particular purpose (Richardson and Midgley, 2007, p. 165), and did not take into consideration such things as social values. Additionally, planners regarded themselves as the experts able to solve all the urban problems. This view of the planner as the expert was heavily critiqued by Jane Jacobs (1961) in her book *The Death and Life of Great American Cities*. Although systems theory in planning has been criticised and has lost favour in planning theory, being replaced at that time by communicative and collaborative planning (de Roo, 2012, l. 3228), "the systems approach represented a considerable advance on the older, inflexible style of planning" (Hall, 2002, p. 231) so typical of modernist thinking.

Although the aim of this study is not to review normative planning of the past and present, it is still useful to consider it and how it influences the way in which we see the city and plan for it. The next section will briefly highlight some of the other views that have brought about a change in thinking, particularly in planning.

2.3.4. Other challenges to the clockwork view of the world

The communicative perspective can be seen as a move away from the view that the planner is the 'expert' whose job it is to provide mainly professional advice and analysis to decision makers (Innes, 1998, p. 52). Systems theory in planning, in which the planner was the 'expert', was thus replaced by communicative and collaborative planning (Batty and Marshall, 2012; Hall, 2002; Todes et al., 2010; Watson, 2002), which, according to de Roo (2012, l. 3268, 2010, p. 970), can be seen as an extreme form of planning on the opposite end of the spectrum to master or technical planning.

Communicative planning was influenced by Habermas's thinking on the public sphere as central to democratic planning. It seeks to solve planning issues through "Interaction (with stakeholders or interest groups), communicating ideas, forming arguments, debating differences in understandings, and finally reaching consensus on a course of action" (Watson, 2002, p. 29). Communicative planning (also called communicative rationality) aims to build consensus, to create circumstances in which discourse between stakeholders with differing views can be achieved. If the right circumstances are created, emancipatory knowledge should be the end result (Innes and Booher, 1999, p. 418). Communicative planning is focused on consensus building through discussion and collaboration and tends to have a focus on local planning and the individual. Each stakeholder should be equally informed about the matter at hand and be given an equal say in the whole decision making process (Innes and Booher, 1999, p. 418).

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Communicative planning is also starting to come under fire from authors such as de Roo (2012, 2010) who argue that it is an extreme form of planning, in direct opposition to the rational planning approach which it heavily critiqued. De Roo (2012, l. 3240) states that an "important criticism arising as a result of the strong commitment to a communicative perspective on spatial planning in the past twenty years concerns a shift away from content and an overwhelming emphasis on processes of planning and the interaction of stakeholders within these processes. This has resulted in a neglect of the content side

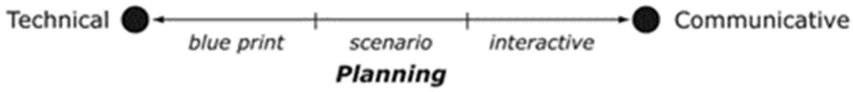

Figure 6: Two extreme forms of planning, namely, Technical and Communicative planning with scenario planning forming in between. Source de Roo (2010, p. 968)

of spatial planning". In other words, there is a need to find a planning approach that is not on the far extreme of rational planning or the other extreme of communicative planning, as seen in Figure 6.

A further response to the critiques on master planning and rational planning, was the development of new forms of planning. According to Todes et al. (2010, p. 415) these were more principle based and include, but not limited to, the following principles:

- "A focus on sustainability;"
- "Integration between sectors and with budgets;"
- "Participatory planning, bringing in a wide range of stakeholders;"
- "understanding markets and producing credible plans, backed by public investment where appropriate;"
- "recognition of the reality of informal settlements and slums;
- "development of contextually appropriate, affordable, strategic and effective forms of planning and land use management; and"
- "pro-poor and inclusive planning, recognising diversity"

From these principles, new normative planning movements and concepts formed in conjunction with communicative planning, (Todes et al., 2010). These include approaches such as the sustainability movement, Just City approach and new urbanism, to name but a few (Watson, 2002).

In recent years the concept of systems has started to gain popularity again. However, the approach of systems' thinking is somewhat different now. Scientists are now starting to use complexity theory in place of systems theory. Unlike systems theory, complexity theory does not seek to impose top-down control onto the system. Rather, it seeks to understand the rules that govern the system from the bottom-up. In many ways, complexity theory includes many existing normative approaches to planning and incorporates them into each other, but it also includes an adaptive approach to planning which co-evolves with the system as it changes (de Roo, 2012, 2010).

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2.4. Complexity

While the previous sections have explored past views of the world and the city, this section seeks to present an alternative approach. This approach being that the world and the cities in which we live are complex and ever-changing systems that are far from equilibrium, yet are not chaotic. To achieve this, a brief history of complexity theory will be presented, after which a description of the different types of systems will be given, as well as a definition of complex and complex adaptive systems. This will be followed by unpacking what makes any system a system by reviewing the properties of complex adaptive systems and how they work together.

2.4.1. History and background

Complexity theory as a science is relatively young and has emerged from systems theory, and chaos theory, and has become a field of study in its own right (Abraham, 2011; Phelan, 2001; Robert, 1999). The study of complexity and complex systems began in the 1920's and some of the concepts of complexity can be found within the literature of general systems theory, cybernetics and system dynamics. Among these, concepts include the ideas of emergence, self-organisation, nonlinearity and adaptability. This is largely due to the fact that complexity as a theory truly only began in the late 1960's and 1970's as a 'child' of systems theory and cybernetics (Abraham, 2011, p. 386). While complexity theory is related to systems theory, these theories should not be confused as they are very different in their approaches. Where systems theory "tended to be represented as static structures, ordered hierarchical systems of parts and their elements that existed in equilibrium and could thus be optimised in terms of their functioning design" (Batty and Marshall, 2012, l. 827), complexity theory argues that systems are in fact far from equilibrium and, because of their dynamics, can transition into a new type of regime (Batty and Marshall, 2012; Gunderson and Holling, 2001).

Batty and Marshall (2012, l. 833) reason that this view that systems are in equilibrium is one of the major failings of systems theory in understanding cities, because what we see when studying the city at any point in time is simply a snapshot of the system, which we assume to be in equilibrium. Intervention, if needed, is then aimed at altering this equilibrium. Complexity theory instead, views the city as a highly dynamic system, with varying equilibriums, that is interacting on many different levels.

2.4.2. Complexity theory

The word *complexity* comes from the Latin word *complexus* which is defined as "Consisting of many different and connected parts"(Oxford Dictionaries, 2015). Alternatively, it can also mean 'entwined' or 'embraced' (Gershenson, 2007, p. 11). Gershenson (2007, pp. 11–12) provides further interpretation by stating that "in order to have a complex you need: (1) two or more distinct parts, (2) that are joined in such a way that it is difficult to separate them. Here we find the basic duality between parts which are at the same time distinct and connected". For this reason, any study of the complex

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means any analytical method on its own which removes or ignores the connectionswill not allow us to understand that which is being studied (Gershenson, 2007, p. 12).

For this reason, complexity theory was developed as a tool to help us to understand the complexity of the world. It does this by studying not only the individual parts of the world but also the connections between them. Complexity theory is the study of complex systems. It differs from systems theory in that it does not necessarily take the same approach of systems theory, whereby everything is connected to everything else and the system is aiming to achieve a state of equilibrium. Rather complexity theory focuses on the relationships between agents and the dynamic nature of the system. Complexity theory studies the rules that agents follow and how these basic rules can produce complex, emergent behaviour in a system (Cilliers, 1998; Coveney and Highfield, 1996; Phelan, 2001; Ramalingam et al., 2008; Stroh, 2005). Furthermore, complexity science seeks to understand the interactions of these agents, as well as the system as a whole, within the system's environment and how these interactions change over time (Cilliers, 1998, p. iix). It is through these interactions that the bottom-up phenomena of self-organisation and emergence occur (Cilliers, 1998, p. ix). The section to follow will look briefly at what we mean when we talk about complexity and complexity theory. It will first do so by arguing what complexity is not and will then consider the different levels of complexity that can be found.

2.4.3. What is (not) complexity?

When describing what a complex system is, it may be useful to first understand what complex systems are not. To do this we can look at Kauffman (1993) and Wolfram's (2002) different classes of systems as a guide to understand complexity and what complexity is and is not (see Table 3 for a description of the different classes). Each of these classes represents not only how complex a type of system is, but also whether or not, and to what extent, the future behaviour of the system can be understood and predicted.

Table 3: Kauffman (1993) and Wolfram's (2002) different classes of systems (Campbell et al., 2011, p. 7; Coveney and Highfield, 1996, p. 98; de Roo, 2012, l. 3268; du Plessis, 2009, p. 262; Peak and Frame, 1994, p. 326).

Systems Class	Description	Type of Planning
Class I: Closed systems	Fixed or static systems with no interaction with the outside world. Clear and direct causal relationship between component parts of the system. The system can be represented by point attractors [6] (close to or at equilibrium), meaning that the system does not change over time and leads to system death. Additionally the system can be described and understood by the whole and its parts.	Modernist planning
Class II: Semi-open systems	These systems are semi-open. These systems tend to settle into a set of predictable, occasionally fluctuating fixed states. Where any disturbance is generally isolated.	Rational choice and scenario planning
Class III: Chaotic systems	These types of systems do not have any predictable patterns of stability and can be described though strange attractors, as	Communicative planning[7]

[6] See Annexure 2, Key concepts of Physical Complex systems (Geyer and Rihani, 2010, p 36 - 41), for a description of the different types of attractors.

[7] De Roo (2012, l. 3268) states that Class III systems can be seen in spatial planning as open networks where actors interact over time in a formal and informal setting. This also being very context specific.

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Systems Class	Description	Type of Planning
	described in Chaos Theory (see Gleick (1998)). They are also sensitive to initial (starting) conditions.	
Class IV: Complex adaptive systems	These systems lie in the edge of order and chaos and because of this, distinct global patterns can occur. These systems can move to different basins of attraction. Additionally, these systems are in a consistent state of 'becoming', meaning that they never reach a fixed state of equilibrium.	Complexity based planning approach

In addition, to Table 3, de Roo (2012, 2010) makes a comparison between these different system classes and compares them to different approaches to planning; class I systems being modernist (blueprint) planning; class II being rational and scenario planning; and class systems III being that of communicative planning. De Roo proposes that a complexity based approach to planning lies within a class IV system as it recognises that systems, and cities, are non-linear and, in order to approach planning in the future, we must accept the benefits of all three approaches but must now include an adaptive approach to planning that emphasises change, flows and evolution/adaption (de Roo, 2012, 2010). For this reason, a complexity based approach to understanding urban change presents itself as the most appropriate.

But the question still remains, what is and is not a complex system? A complex system is not: simple, complicated, disorganised (disorganised complexity) or chaotic. Below is a short outline of what complexity is not, after which a description of what complexity is will be discussed in the beginning of the next section.

2.4.3.1. Complexity is not simple (Class I Systems)

"Simple" and "complex" may seem easy to differentiate but Cilliers (1998) reasons that, when looking at systems, this may not always be the case. He maintains, "Many systems appear simple, but reveal remarkable complexity when examined closely (e.g. a leaf). Others appear complex, but can be described simply" (Cilliers, 1998, p. 2), e.g. some machines. Cilliers (1998, p. 3) goes on to say the "distinction between complex and simple often becomes a function of our 'distance' from the system". This raises the question whether complexity is determined by the point of view of the observer? The simple answer would be 'no'. Complex systems do have properties and characteristics that are not dependent on the perspective of the observer (Cilliers, 1998).

To make it easy for us, we can say that a simple system is comprised of two or three variable problems, i.e. the rotation of the planets (Johnson, 2002) and that "in simpler systems, feedback may be linear, predictable and consistent"(Ramalingam et al., 2008, p. 15). This brings in the notion that simple systems behave in a far more predictable manner due to the fact that the feedback processes are linear, i.e. there can be a direct cause-effect relationship.

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2.4.3.2. Complexity is not complicated (Class II systems)

"Complicated" and "complex" are words that are often used interchangeably in everyday speech but, when we consider these words in systems, they take on very different meanings. A complicated system is a system that is at or close to equilibrium; a marble settling at the bottom of a bowl is an example of an equilibrist system (Geyer and Rihani, 2010). Complicated systems can be comprised of many different parts, but the fact that the system can be accurately analysed makes it merely complicated and not complex (Cilliers, 1998; Geyer and Rihani, 2010). Complex systems on the other hand are far from equilibrium.

2.4.3.3. Complexity is not disorganised

According to Skyttner (2005, p. 75), unorganised complexity "can only refer to non-living systems where the number of variables is very large and in which each variable has a totally unpredictable or unknown behaviour". Johnson (2002, pp. 46–47) describes this type of complexity as being characterised by millions or billions of variables. Due to the sheer number of variables, these systems can be approached only from the methods of probability theory and statistical mechanics. These methods have been used, for example, to explain the behaviours of gasses. Complexity is not chaotic (Class III systems)

Chaotic systems can be simply defined as the movement of a system away from order (equilibrium) (Stroh, 2005). Chaotic systems have some of the characteristics of a complex system, i.e. they are non-linear dynamic systems (they change over time) that can exhibit complex behaviour. However, the complex behaviour they display is chaotic, non-repetitive, unstable, and can have simple causes (Valle, 2000). Chaotic systems are sensitive to initial conditions, meaning that small changes to the starting point can have large effects on the system (Cilliers, 1998; Coveney and Highfield, 1996; Sardar et al., 1999; Valle, 2000).

Complex systems (Class IV systems)[8], as opposed to chaotic systems, can be said to lie on the edge of chaos, on the border between order and chaos (de Roo and Silva, 2010, l. 914), see Figure 7. This is also the point where the system is at its most innovative (Beinhocker, 2006, p. 157; Valle, 2000, p. 2).

Complex systems tend to become more complex as they move through time. The more complex they are, the more complex they tend to become. However, It is only a tendency for complex systems to become more complex; they can also become less complex (Geyer and Rihani, 2010, pp. 45–46). The increase in complexity happens as the different layers of interconnections and adaptions build up. This must happen at a rate that the system can manage and cannot be speeded up significantly or artificially. Systems need time to generate a sufficient amount of *depth* in complexity. Systems with greater depth have no guarantee of surviving. However, the tendency is for more diverse and adaptive systems to survive (Geyer and Rihani, 2010; Holland, 1996; Page, 2011).

[8] Like chaotic systems, complex systems are also sensitive to initial conditions (Geyer and Rihani, 2010).

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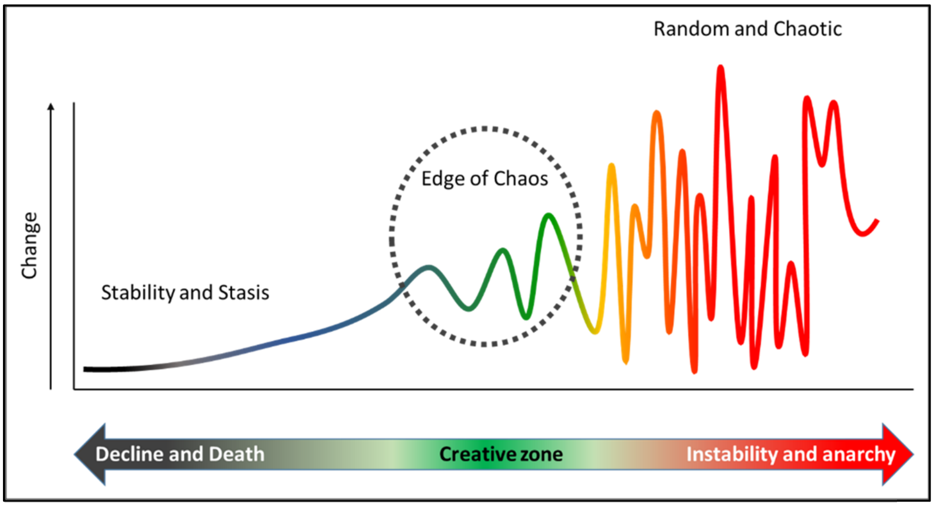

Figure 7: Complex systems are located in the region between order and chaos. This area is also where the most innovation happens

2.5. Complex adaptive systems

If a complex system is not simple, complicated, disorganised or chaotic; what then is it? Class IV systems or complex (adaptive) systems will be discussed in detail in this section. This will be done by first defining what a *complex system* is, after which the focus will shift to *complex adaptive system*s and their definition.

2.5.1. Defining complex

There are many definitions of a complex system[9] but, if we consider the main characteristics of some of these definitions (Annexure 4), we can create a useful definition of a complex system (as well as a complex adaptive system). From the table in Annexure 4 we can identify some key recurring, concepts. These being:

- Complex systems consist of many agents
- Agents interact with each other
- Interaction happens over a network of some kind
- Agents have dynamic, non-linear, interactions
- Interactions between agents leads to emergent, complex behaviour over time
- The agents follow rules
- The system is open to, and interacts with, its environment
- Systems can have local instability, but have global stability

From these key concepts, we can build our own definition of a complex system for the specific purpose of this study.

[9] See Annexure 4 for various authors' definitions of complex systems

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From the above definition we can see that, like our 'base definition' of a system, a complex system is comprised of agents that interact with each other to produce a particular behaviour. However, unlike the base definition, complex systems interact in a non-linear manner, which produces the unique behaviour of each complex system.

The second distinction is that a complex system interacts with, and is open to, its environment (Innes and Booher, 2010). Meaning the environment in which the system finds itself has an impact on the system's behaviour. An example of this could be a city located near a volcano. When the volcano is dormant, the city may behave in a particular way but, if the volcano becomes active, the city will respond accordingly. Another example may be how a country's economic policy may change depending on the international economic trends.

The final distinction, and perhaps the most important one is, when studying complex systems, the agents within that system follow rules. These rules are often simple; however, these simple rules can lead to complex behaviour (Holland, 1996; Page, 2011).

2.5.2. Defining complex adaptive systems

The definition of complex systems can be taken further when distinguishing between "*complex systems* – systems in which the entities follow fixed rules – and *complex adaptive systems* – systems in which the entities adapt" (Page, 2011, p. 25). If we take this distinction between complex systems and complex adaptive systems into account, it will require a rethink of the current definition of complex systems to include the adaptive nature of some systems.

Brownlee (2007, p. 2) argues that "There is no [one] clear definition of a complex adaptive system". If Brownlee's statement is to be taken as true, which in this case it will be, the definition below should not be considered as '*the definition'* of complex adaptive systems, but rather a definition for use in this study. A complex adaptive system for the use of this study will be defined as follows:

A complex adaptive system is a system that is comprised of many diverse agents that interact with each other in a non-linear, dynamic manner. The interaction and behaviour of the agents are governed by a set of rules. If the agents adapt the rules that they follow, then there will be an adaption of the agent's behaviour. In a complex adaptive system, the system itself does not adapt but rather the agents adapt, leading to system-wide adaption. Each agent adapts to changes of the agents around it. Complex adaptive systems are open to and interact with their environment, as well as other systems. It is through these interactions and adaptions that a complex adaptive system creates complex temporal behaviour (Beinhocker, 2006; Brownlee, 2007; Geli-Mann, 1994; Health Foundation, 2012; Holland, 1996, 1992; Innes and Booher, 2010; Lucas, 2006; Page, 2011).

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The key components of the definition are that a complex adaptive system:

- Consist of many diverse agents
- Agents interact with each other in a dynamic, non-linear, manner
- Interactions between agents lead to complex behaviour over time
- The agents follow rules
- The agents adapt the rules that they follow
- The adaption of rules leads to a change in the agent's behaviour.
- Agents adapt to the adaption of other agents within the system, which results in a system wide adaption
- The system is open to, and interacts with, its environment

Brownlee (2007, p. 2) goes on to say, while no one definition for complex adaptive systems exists, there are, rather, common "sets of parsimonious principles and properties, with, in many cases, different researches in the field defining their own nomenclature". So, if one is truly to begin to understand what complex systems and complex adaptive systems are, it would be prudent to examine the common properties, components and characteristics of complex adaptive systems.

2.6. Properties of complex adaptive systems

Complex systems tend to become more complex as they move through time. The increase in complexity happens as the different layers of interconnections and adaptions build up. This must happen at a rate that the system can manage and cannot be speeded up significantly or artificially. Systems need time to generate a sufficient amount of depth in complexity. Systems with greater depth have no guarantee of surviving; however the tendency is for the more diverse and adaptive systems to survive (Geyer and Rihani, 2010; Holland, 1996). As mentioned above, complex adaptive systems have a set of common properties that characterise all complex adaptive systems (Brownlee, 2007, p. 2).

The various properties of complex adaptive systems have been summarised in Table 4. These are the various properties of complex adaptive systems (CAS) as described by various authors (see Annexure 2 for a detailed summary of various authors' description of the properties and characteristics of complex systems). Each of these properties will be discussed in the following text.

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Table 4: Properties and characteristics of complex adaptive systems

Property of CAS	Description	Source
Agents	Agents are the elements or '*things'* that make up the system. Agents interact with each other through relatively simple rules that can adapt as and when needed. Agents are goal orientated and capable of solving problems on their own. Agents ca aggregate together to form higher level agents	(Beinhocker, 2006; Holland, 1998, 1996; Innes and Booher, 2010; Johnson, 2002; Page, 2011)
Interactions and Flow	Interactions between the elements of a system that allow for adaption happen through the process of feedback. Feedback is the mechanism or rule(s) that enables the flow of information, signals and resources within a system, which in turn allows the system to function. A characteristic within complex systems is that feedback between elements happens in a non-linear manner, helping to self-organise produce the systems emergent behaviour	(Folke, 2006; Holbrook, 2003; Irwin et al., 2009; Meadows, 2008; Richardson et al., 2001; Rosser, 2011; Sanders, 2008; Senge, 2006)
Adaption	Adaption in CAS happens at the level of individual agents and not on a system level. Each agent adapts to changes in its environment and its neighbours. This causes system wide adaption.	(Brownlee, 2007; Folke, 2006; Gunderson and Holling, 2001; Holland, 1996, 1996, 1992a; Lang, 2012; Shan and Yang, 2008; Walker et al., 2004)
Self-organisation	The ability of a system to structure itself (through its non-linear interactions), without external interventions, to create a new structure or behaviour.	(Meadows, 2008; Richardson, 2004b; Roggema, 2012; Ryan, 2007)
Emergence	Emergence refers to the higher-order system pattern or behaviour that is created through the process of self-organisation.	(Choi et al., 2001; Funtowicz and Ravetz, 1994; Johnson, 2002; Lansing, 2003; Richardson, 2004b; Roggema, 2012; Ryan, 2007; Sanders, 2008)
Hierarchies	Through the bottom-up process of aggregation CAS form a series of nested or sub-systems that aggregate together to form a higher level sub-system. In essence CAS are made up of systems within systems. These various levels of systems interact with each other across the hierarchy.	(Cilliers, 2008, 1998; Gunderson and Holling, 2001a; Health Foundation, 2012; Holland, 2012; Ostrom, 2007; Richardson, 2005a, 2004b; Ryan, 2007; Sanders, 2008; Skyttner, 2005; Walker et al., 2004)
Diversity	CAS are made up of a large number of diverse elements. These elements can differ in terms of their type, size, function and composition, to name but a few	(Holland, 1996; Page, 2011; Sanders, 2008)
Redundancy	Redundancy refers to a system having backups of parts, resources, paths or functions of the system	(Allen, 2005; Meadows, 2008; Page, 2011; Richardson, 2004b)
Resilience	Resilience refers to the amount of disturbance or shock that a system can take without moving into a different attractor basin. It also refers to the ability of a system to adapt and self-organise to changes in its environment.	(Davoudi et al., 2012; Folke, 2006; Folke et al., 2004; Gunderson and Holling, 2001; Kinzig et al., 2006; Roggema, 2012; Salat and Bourdic, 2012a)
Co-evolution	CAS are open to, interact with and adapt to their environment. Through this process CAS change their environment, which in turn cases them to adapt to the new environment. This process can also be called co-evolution, as the systems agents adapt to the adaptions that take place in the environment around them. This process is also strongly linked to the process of self-organisation and emergence.	(Chu et al., 2003; Cilliers, 2005a, 1998; du Plessis, 2008a; Holland, 1992a; Innes and Booher, 2010; Nel, 2009; Roggema, 2012)

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2.6.1. Agents and interactions

According to Chiong and Jankovic (2008, pp. 4–5), an agent can be described as "an autonomous, problem solving computational entity capable of effective operation in dynamic and open environments". In other words, agents are *things* that make up/populate a complex system and are capable of solving problems on their own. An example of an agent can be a person within an urban system.

The characteristics of agents are autonomy (they can carry out actions of their own), goal-orientation, communication (they send and receive signals from each other), the ability to learn, adaption, and to take action within an environment (Chiong and Jankovic, 2008, pp. 4–5). The interaction between agents is non-linear and is governed by a set of simple rules (strategies or schema), e.g. IF *a* happens THEN do *b*. However, these rules lead to the complex behaviour typical of CAS (Batty, 2007; Choi et al., 2001; Cilliers, 1998; Geyer and Rihani, 2010; Holland, 2012, 1996, 1992a, 1992b; Innes and Booher, 2010; Page, 2011).

To illustrate how simple rules can result in complex behaviours, the game of chess will be used as an example together with a computer simulation called the '*Game of Life*', developed by John Conway. The rules that govern a game like chess are simple but they produce a game that is incredibly complex. Each type of chess piece follows its own set of rules that govern the movement of the various pieces. For example, a pawn has a different set of movement rules to those of a knight or queen, thus giving them different abilities. The more mobile the chess piece, the greater its threat to the other player.

To explore this further, the example of a pawn and a queen will be used. A pawn has the most basic set of rules: it can move only one space forward and can take another piece only if it is diagonally in front of it (see Figure 8a). This has a limited dynamic in the game when compared to a queen, which can move forward, backward and diagonally for as many unobstructed squares as desired in any direction (see Figure 8b). This greater range of movement makes a queen a dangerous piece adding an extra dynamic to the game. It is the respective rule sets of each individual piece that govern the dynamics of the game.

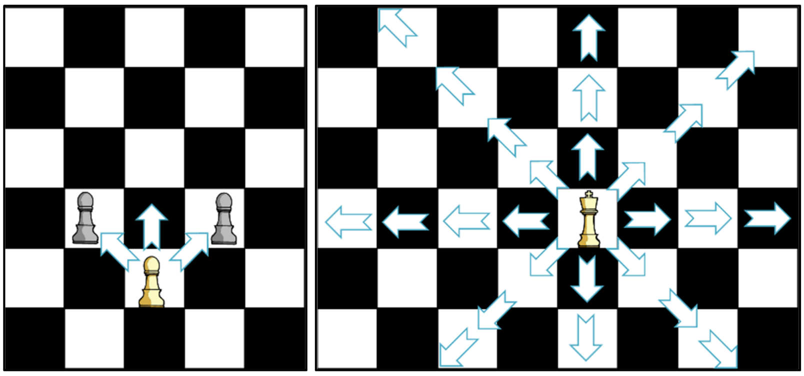

Figure 8: (a) Moves of a pawn (left) and (b) moves of a Queen in chess (right).

The second example of how simple rules can lead to complex behaviour is that of the computer simulation called the *Game of Life*. This is a cellular automaton that uses a set of mathematical rules to determine which cells, on a two dimensional grid, 'live', 'die' or 'multiply (Callahan, 2005).

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In the simulation, each cell interacts with each of its neighbouring cells - horizontally, diagonally and vertically adjacent to any specific cell. Depending on the initial starting conditions, the cells will form various patterns on the grid. Some patterns are symmetrical; others repeat themselves as they move along the grid, while some lead to death (Callahan, 2005; Chris Lipa, n.d.; Gardner, 1970; "John Conway's Game of Life," n.d.). The rules that govern the Game of Life are as follows[10]:

For a space that is 'populated':

"Each cell with one or no neighbours dies, as if by loneliness. Each cell with four or more neighbours dies, as if by over-population. Each cell with two or three neighbours survives" (Gardner, 1970).

For a space that is 'empty' or 'unpopulated'

"Each cell with three neighbours becomes populated" (Gardner, 1970).

From these few simple rules, a series of possible patterns can emerge. Some examples of these patterns are shown in Figure 9.

An early example of an attempt to identify rules in society is found in the 1651 publication, *Leviathan* by Thomas Hobbes (Ball, 2005, pp. 7–37; Hobbes, 2003). In this work, Hobbs attempted to create a political theory for society. His greatest flaw was not that he wanted to discover the rules that govern social life; but rather that he used a mechanistic world view to do so, thus ignoring the importance of the underlying interactions and complexities. The rules in a social system can include values and beliefs, the laws of a nation, local customs, etc.

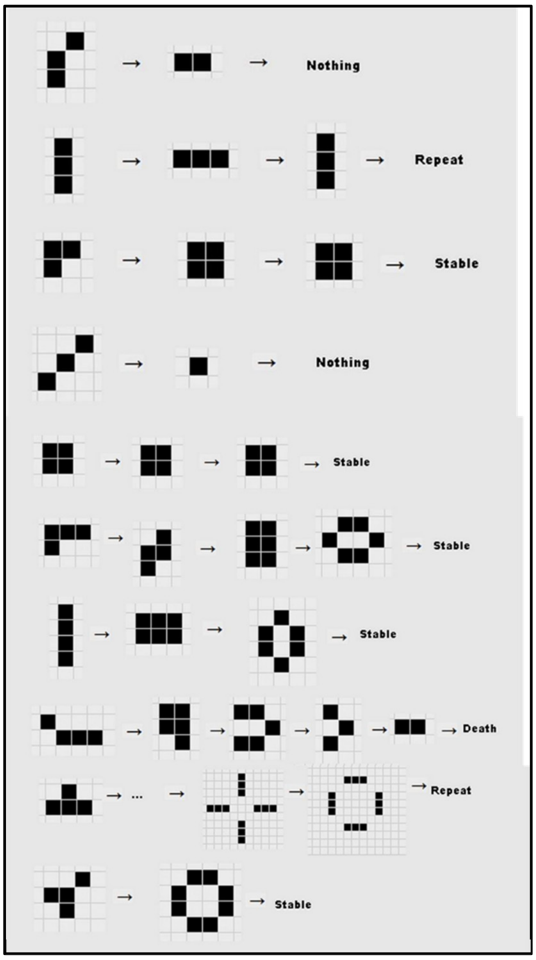

Figure 9: Some examples of patterns that can be found in the game of Life. Where it says 'Stable' the pattern does not change, 'Repeat' the pattern changes between the last two images and 'Death' or 'Nothing' the cells 'die'. Source ("John Conway's Game of Life," n.d.)

The **interactions** within in CAS are dynamic and nonlinear. Nonlinearity refers to their seldom being a direct cause-effect relationship, action taken and the result of that action (Cilliers, 1998, p. 4; Meadows, 2008, p. 187). Because of this, one cannot predict the long-term behaviour of a complex system (Cilliers, 1998; Holland, 1992b). Due to the nonlinearity of the interactions between agents within the system, a CAS cannot be described by adding up the sum or average of its individual parts.

[10]For a visual description of the rules see Stephen Hawking's The Meaning of Life (John Conway's Game of Life segment) available at: https://www.youtube.com/watch?v=CgOcEZinQ2I&feature=share&list=FLwikA_t8e6TSJW-L-lAHkKw

It is, rather, the *product* of the distinct variables that helps us describe the CAS (Cilliers, 1998; Holland, 1992b). Aggregating some variables helps to simplify the calculations needed to describe the nonlinear equation for a CAS. In other words, "nonlinear interactions almost always make the behaviour of the aggregate more complicated than would be predicted by summing or averaging" (Holland, 1996, p. 23).

Interactions between agents are generally short range, meaning that most of the information is sent or received from its immediate neighbours. While long range interactions are not impossible, they are less likely to occur due to practical constraints (Cilliers, 1998, p. 4). This does not mean that there is a narrow range of influence. As there are a vast number of interactions between agents, the flow of information from one agent to another can usually be covered in a few steps. As a result of this, the agent's influence can be modified, enhanced, suppressed or altered as it moves among agents (Cilliers, 1998, p. 4). It is also important to note that because of the short range interactions "Each element [or agent] in the system is ignorant of the behaviour of the system as a whole, it responds only to information that is available to it locally. This point is vitally important. If each element 'knew' what was happening to the system as a whole, all of the complexity would have to be present *in that element*" (Cilliers, 1998, p. 4-5 [Cilliers' italics]). Instead, it is the richness of the interactions between agents that allows for complexity to form. Because of the short range that interactions tend to have within a system, it is important to study the way that information flows within a system This is determined by the structure and strength of the network (Boccaletti et al., 2006; Choi et al., 2001; Cilliers, 1998; du Plessis, 2008a; Neal, 2013; Newman, 2003). Although the agents within a system can change, the structure often remains the same (J. Hillier, 2012, l. 1083).

This can be seen in complex systems like ant colonies and cities, which often lose and gain new ants or people (due to deaths and births), yet still remain the same colony or city (Johnson, 2002, pp. 29–33). However if a system does change its structure, it means that there is a change in how the information moves within that system, which can affect the content, manner of transfer and timeliness of the information between agents as well as the overall behaviour of the system (Hjorth and Bagheri, 2006).

2.6.2. Adaption

Linked strongly to the agents is the concept of adaption. The simple rules used by agents within CAS can change as the environment and agents around them change. This is called adaption (Cilliers, 1998; Geyer and Rihani, 2010; Holland, 2012, 2006, 1998, 1996, 1992b; Innes and Booher, 2010; Page, 2011). The agents that adapt are called adaptive agents, for obvious reasons. When a CAS adapts, it is not the system as a whole that adapts, instead adaption occurs at the level of the individual agent. Meaning that it is the agents within a system that adapt, causing a system wide adaption (Anderies and Norberg, 2008; Chiong and Jankovic, 2008; Gerrits, 2012; Geyer and Rihani, 2010; Holland, 2012, 1996, 1992b; Johnson, 2002; Miller and Page, 2007; Page, 2011). Adaption in agents is guided by experience that the agent draws from its memory as it learns to deal with new challenges (Chiong and Jankovic, 2008, p. 4; Holland, 1996, pp. 6–10). Adaptions take place at different time scales for

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different agents. For some, adaption may take a few hours or days, as seen with the immune system, while others, like firms/companies, may take months or years to adapt. Adaptive changes in ecosystems may take many hundreds or thousands of years (Holland, 1996, p. 10).

Adaptive agents can aggregate together to form a higher level agent, called an aggregate agent (see Figure 10), whose behaviour is determined by the integration of its component agents (Holland, 2012, p. 2). An example of aggregation is how all the cells in the body aggregate together to form the various organs and these then aggregate further to form the body. Alternatively, we can also say that individual people can aggregate together to form a company or a government. Different levels of aggregation can also be seen in institutions such as universities. At the lowest level, a university is made up of students and staff, which then can be grouped together to form various departments, which in turn can be grouped together to form schools. These can then be further grouped to form faculties which then group together to form the university. Aggregation, in combination with self-organisation, is also one of the ways in which CAS build hierarchies (Levin, 1998, p. 432).

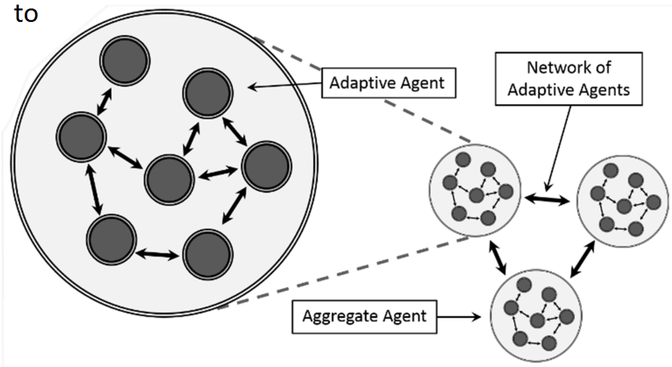

Figure 10: A network of adaptive agents (Left) aggregate to form an aggregate agent, which then forms part of a higher order network. Adapted from Holland (2012, p. 2)

2.6.3. Flows

Information flows within a CAS move over a network that varies over time (Holland, 1996, p. 23). The network is made up of nodes (also called vertices in networks theory) and connectors. The nodes are the agents within the network and are the processors of information. The connectors link the nodes together and allow for the movement of information. This creates the interactions between the nodes of the CAS (Boccaletti et al., 2006; Holland, 1996; Newman, 2003). As such, we can say that CAS have node >> connector[11] >> resource movements, as described in Figure 11, (Holland, 1996; Meadows, 2008; Wilson, 2010). The flows and structure of CAS networks are never static, as nodes and connectors may form or vanish as the agents within the CAS adapt, or fail to do so. As a result, the patterns and structures that form

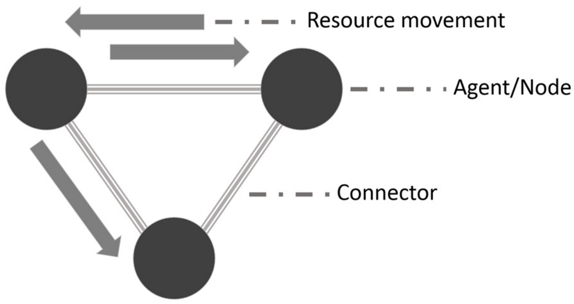

Figure 11: A basic illustration of node, connections and resources within complex adaptive systems

[11] Nodes and connections can also be referred to as vertices and edges, respectively, in terms of networks and graph theory (Boccaletti et al., 2006; Cardillo et al., 2006; Neal, 2013; Newman, 2003; Porta et al., 2006a, 2006b)

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within a CAS reflect the changing adaptions that occur over time as the system gains experience (Boccaletti et al., 2006, p. 197; Holland, 1996, p. 23).

Tags[12], a term used by Holland (1996, 2012, 1998, 1992b) to describe the mechanism that facilitates the formation of aggregates in a CAS, often describe the network by defining the major/critical connections within the CAS. This mechanism takes on an important role as the adaptation process transforms a CAS. Tags that promote useful interactions are encouraged and tags that break down connections are discouraged. As such the useful tags spread and the disruptive tags are eliminated from the system (Holland, 1996, p. 23). This allows for the system to function more effectively.

2.6.4. Self-organisation

Self-organisation is a property of a complex system that describes the process by means of which complex systems can spontaneously organise themselves from what can be seen as chaos, randomness or disorder into something that is ordered and structured without any direct internal or external influence (Helbing, 2009; Meadows, 2008; Mitchell, 2009; Richardson, 2005b; Roggema, 2012; Sanders, 2008). Self-organisation can alternatively be described as a process "where macro-scale patterns of behaviour occur as the result of the interactions of individuals who act according to their own goals and aims and based on their limited information and perspective on the situation"(Ramalingam et al., 2008, p. 49). As these simple, nonlinear, rules create, complex behaviour that is difficult to predict, the macroscopic behaviour can be seen as emergent (Mitchell, 2009, p. 13).

2.6.5. Emergence

Emergence, as described by Johnson (2002, p. 82), is "The persistence of the whole over time – the global behaviour that outlasts any of it component parts – [and] is one of the defining characteristics of complex systems". Batty (2007, p. 51), on the other hand, describes emergence as the process by which "local action has led to global patterns whose form cannot be anticipated from a knowledge of the rules that govern the processes of change". Johnson (2002, p. 18) further describes emergence as the "movement from low-level rules to higher-level sophistication…[when]… agents residing on one scale start producing behaviour that lies one scale above them". From these descriptions, it can be said that higher level system behaviour emerges from the local interactions of the individual agents, including aggregate agents, and that these interactions are governed by simple rules. In addition, Miller and Page (2007, p. 46) indicate that the emergent aggregate behaviour "should be immune to reasonable variations in the individual behaviour", meaning that the emergent behaviour should be able to continue within an environment where there are changes, within reason, to the individual

[12] Tagging is a widespread mechanism for the formation of aggregates. It acts as a means of boundary formation by facilitating selective interactions within a CAS. CAS use tags to manipulate symmetries and ignore some details while bringing our attention to others. Tags allow us to see and take action on things previously hidden by symmetries. Tags allow agents within a CAS to select amongst agents or objects that would normally be invisible or indistinguishable. Well established tag-based interactions create a basis for a CAS to filter information, specialise and cooperate. Further tagging allows for meta-agents and organisations to emerge, even though their components are consistently changing (Holland, 2012, 1998, 1996, 1992a).

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agents' behaviour. This is supported by Johnson (2002, p. 82) who argues that "The persistence of the whole over time – the global behaviour that outlasts any of it component parts – is one of the defining characteristics of complex systems".

Emergent behaviour is often unpredictable, even if we know the rules that govern the interactions (Batty, 2007, p. 51). It is largely because of the way a complex system emerges, through the large number of nonlinear interactions which lead to self-organisation[13], that there is limited predictability of a complex system's behaviour. It is also why there is so much study on the phenomenon[14] (Geyer and Rihani, 2010; Heylighen et al., 2006; Human and Cilliers, 2013; Nel, 2009). Because a complex system emerges through self-organisation, we can say the system 'becomes' instead of 'is' (Roggema, 2012, p. 68) and that the emergent behaviour can form higher level behaviour, which can then give rise to even higher level behaviour (Railsback, 2001, p. 50). This brings us to the next property of a CAS, that of hierarchies.

2.6.6. Hierarchies

Hierarchies in CAS are not the same as typical organisational hierarchies of top-down command (Cilliers, 2008; Gunderson and Holling, 2001; Johnson, 2002; Meadows, 2008). In CAS, hierarchies form naturally through the process of self-organisation (Levin, 1998), emergence (Holling et al., 2002; Johnson, 2002), and the aggregation associated with emergence (Holland, 1996, p. 12).

A hierarchical system has a series of interconnected sub-systems, which in turn have sub-systems of their own, and so on, Figure 12, (Holland, 2012; Johnson, 2002; Mitchell, 2009; Simon, 1962). These sub-systems are often called nested systems, as the lower level systems are nested within the higher level system (Folke, 2006; Gunderson and Holling, 2001; McShea, 2001; Mitchell, 2009; Norberg and Cumming, 2008; Sales-Pardo et al., 2007; Wu and David, 2002).

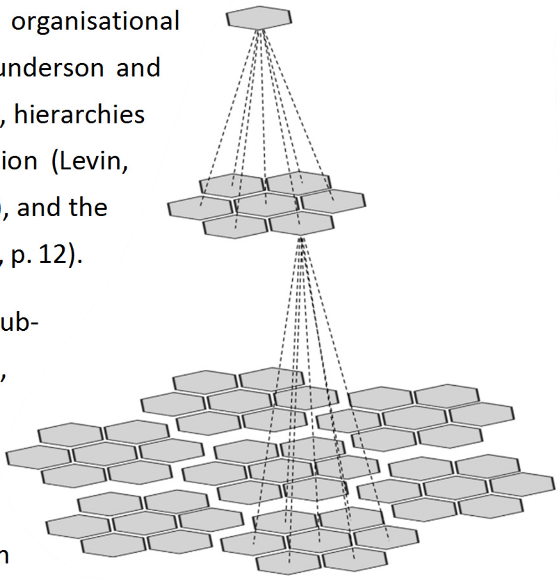

Figure 12: A basic outline of the bottom-up process of aggregation that creates hierarchies of nested sub-systems within complex systems

In his paper, *The Architecture of Complexity*, Simon (1962) presents an argument for why hierarchies are important. The first part of his argument is that the nested nature of systems makes it easier for complex systems to be created. The example that Simon (1962, p. 470) uses is that of the parable of the two watchmakers. Each of the watches that they make consists of 1000 parts and each watch is

[13] This also includes the fact that systems are open to and interact with their environment (Cilliers, 2005a; Geyer and Rihani, 2010; Human and Cilliers, 2013; Innes and Booher, 2010).
[14] According to Mitchell (2009) and Railsback (2001) some of the main questions of complexity comes from asking about how self-organisation and emergence comes about. Many books and papers in different fields have been written about both topics, see Funtowicz and Ravetz (1994), Holland (1998) and Johnson (2002) on emergence and Allen (2005), Barthelemy et al. (2013) and Portugali (1997) on self-organisation

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of equal quality and complexity. Both of the watchmakers are very popular and the phones in their workshops ring frequently as customers ask for new orders. The difference between the two watchmakers is that the one watchmaker builds a watch from scratch. Each time the phone rings and he gets up to answer it, he loses all the progress he has made on a partially assembled watch, as the watch falls apart. The other watchmaker designs his watches so that he can make subassemblies. Each of these subassemblies can then be put together to create a larger subassembly. This continues until the watch is complete. The second point Simon (1962) argues is because of this modular nature of complex systems, they will be more efficient than they would if there was no hierarchy and an algorithm can be developed to ensure the movement of information through the system.

Lastly, Simon (1962, p. 478) argues that hierarchies create redundancy within a system because (1) "Hierarchic systems are usually composed of only a few different kinds of sub-systems, in various combinations and arrangements" which allows the system easily to replace or recreate a part of itself if it gets damaged or destroyed. (2) Complex systems are nearly decomposable, meaning that they can be partly taken apart into their component sub-systems[15] (Meadows, 2008, p. 83), and (3) the structure of the system lends itself to being more redundant as a 'broken' or missing link within the system can be replaced or its function duplicated.

The structure of hierarchical sub-systems, as described by Wu and David (2002, p. 9), can be seen to be made up of vertical structures, composed of different levels, and horizontal structures. Horizontal structures are made up of holons, an idea first introduced by Koestler (1967) in his book *The Ghost in the Machine*. Holons are the parts that make up a nested hierarchy (du Plessis, 2008a, p. 79), such as provinces/counties within a country or individuals in an organisation (Norberg and Cumming, 2008), and can be thought of as a "*structuring* entity (it includes its own parts) as well as *structured* (it is part of another holon)" (Mella, 2009, p. 11 [Mella's italics]). In other words, holons can be seen as wholes, on their own. At the same time, they are part of another entity. In addition, holons are "not the structure but of the structure, a centre for the relationships with the other component, subordinate and composed, and superordinate structures" (Mella, 2009, p. 10).

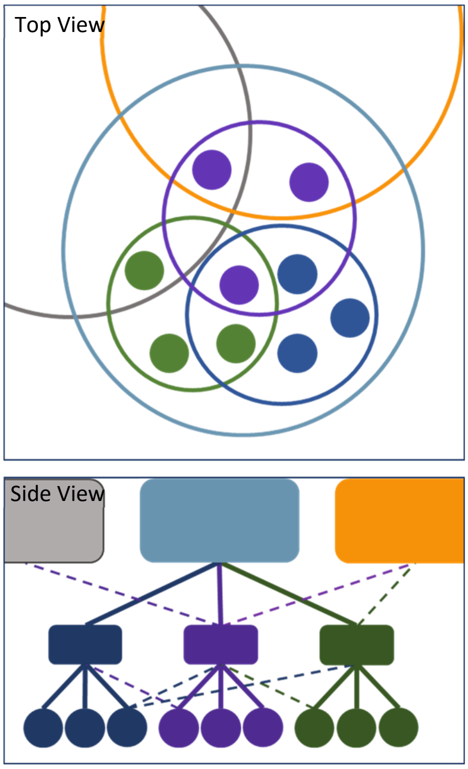

Figure 13: Visualisation of a hierarchical system containing vertical and horizontal structures. The dashed lines (side view) indicating weaker connections between holons (these are represented in the *top view* by where the circles overlap.

Figure 13 visualizes this. Each component is a whole while simultaneously forming part of a larger entity. The higher level components provide structuring constraints on the

[15] Discussed in more detail in, Chapter Four

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lower level components. Additionally, the interaction between the components within holons are stronger and more frequent than the interactions between holons (Wu and David, 2002, p. 9). Just as each part (different coloured circle) can be seen as a whole when looking at the lower levels of the hierarchy, it can similarly be seen as a part of a larger whole when looking at the higher levels of the hierarchy.

Part of the theory around hierarchies and holons argues that higher level holons exert constrains on lower level holons (e.g. exerting sub-system boundary conditions), while lower level holons are constituents of the higher level holon (du Plessis, 2008a, p. 79; Norberg and Cumming, 2008, p. 250). Du Plessis (2008a, p. 79) writes that “Lower levels can influence higher levels through upward causation, and higher levels can control or influence what happens at lower levels through downward causation”. The idea of interaction across different hierarchical levels has been developed further by Gunderson and Holling (2001) in their concept of Panarchy (this is discussed in more detail in Chapter 5). Panarchy emphasises that hierarchies are maintained through the interaction of the processes at different levels and that the patterns and processes that occur at lower levels are contained at the higher level, e.g. people within an organisation or cells within an organ (Norberg and Cumming, 2008, p. 250). Furthermore, Gunderson and Holling (2001) reason that changes at one level of the system can have cascading effects on higher and lower scales.

In essence, hierarchies allow us to visualise and arrange the components in a CAS through the idea that that there are “predictable relationships between system components that occur at different levels” (Norberg and Cumming, 2008, p. 251). Higher level sub-systems are characterised by slower movements, responses and changes compared to lower level sub-systems (Gunderson and Holling, 2001; Holling et al., 2001c; Norberg and Cumming, 2008; Wu and David, 2002). Interactions and connections within sub-system components are stronger and more frequent than those between sub-systems at the same level and at levels above and below (Meadows, 2008, p. 83; Wu and David, 2002, p. 9). It is through these various strengths and frequencies of interactions that natural boundaries are formed between sub-systems (Meadows, 2008, p. 83).

2.6.7. Diversity

Diversity can be articulated as having a range of types of functions or parts. It can be expressed as variations between one type of element, or different types of elements (e.g. different types of species in an ecosystem or different modes of transport in a transport system, or a range of ecosystem services all performing a similar function of retarding run-off and lowering flood peaks), as well as differences in the arrangement of the different types (Ahern, 2011; Gunderson and Holling, 2002; Page, 2011).

Diversity is vital for any CAS as it helps to create niches within a system (Holland, 2012), builds resilience and adaptability (Gunderson et al., 2008), creates competition and innovation (Beinhocker, 2006; Huys and van Gils, 2010), and helps to create complexity (Page, 2011). Diversity in CAS is created from progressive adaptions, changing conditions and imperfections (Holland, 1996, 1992a; Johnson, 2002; Norberg and Cumming, 2008). In social systems, it is created through innovation and foresight

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(Norberg and Cumming, 2008, p. 10). However, diversity is not random or accidental. It depends on the interactions of various agents and the context in which they find themselves (Holland, 1998, p. 27). Each agent, or type of agent, fills a particular niche. Each niche is defined by the interactions of other agents with that agent. If that agent is removed for some reason, in the process creating a ‘gap’, the system will respond by creating adaptions in other agents until that gap is closed. The gap could be filled by one or many agents (Holland, 1998, p. 27).

Additionally, diversity helps to create complexity. If one system has more diverse agents than another (although they have the same number of agents), the system with the larger diversity of agents has a higher chance of being more complex than the other. This is because the more diverse agents there are, the higher the possibility of unique interactions forming between agents and the more complex the emergent behaviour of that system is likely to be as a result (Page, 2011, pp. 33–45).

The usual way that diversity is measured is by simply counting the different types of agents or functions within a CAS. However, this is a limited and simplistic view of diversity (Levin, 1998, p. 433). Within a CAS, diversity can be seen in many different ways. Page (2011) says diversity within complex systems can be viewed, studied or categorised in three primary ways.

The first of these is diversity in type. This can also be expressed as *variation* and denotes the “differences in the amount of some attribute or characteristic” (Page, 2011, p. 20). For example, if we look at Figure 14 we can see five plain circles. All the circles are identical except for their size. The diversity is purely in terms of the size of circle. Variation is often measured in terms of criteria such as length, width, height, size, etc. (Page, 2011, p. 21).

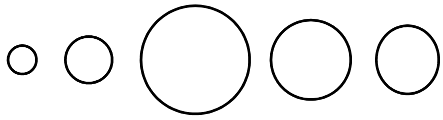

Figure 14: Diversity within type. Adapted from Page (2011, p 21)

Figure 15: Diversity across types. Adapted from Page (2011, p 22)

The second form of diversity that Page (2011) discusses is diversity across types. This considers the differences between various types, for example, types of plants, animals, or foods. This form of diversity can also be looked at in terms of functional diversity (Page, 2011, p. 22). To help illustrate this, Figure 15 presents four objects, starting from the left is a pizza, a coin, a plate and a bicycle wheel. Each of these objects is round but each serves a very different function (Page, 2011).

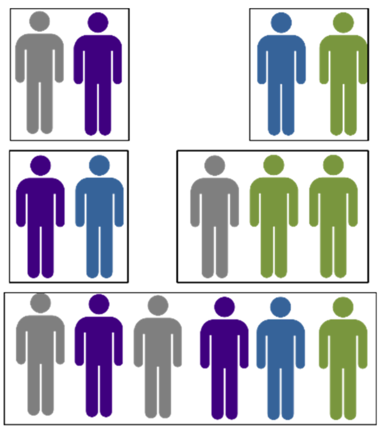

Figure 16: Diversity of composition

The final type of diversity that Page (2011) describes is diversity of composition. This type of diversity can be seen in different compositions of population groups. For example, in Figure 16, there are five different groups of people. Each group is made up of different types and numbers of people. As a result of the

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interactions between the people, we can expect to find unique emergent properties for each group (Page, 2011, p. 23).

An increase in diversity of a particular function, i.e. transport also facilitates the creation of redundancy within that function (Page, 2011, pp. 229–230). "A diverse system with multiple pathways and redundancies is more stable and less vulnerable to external shock than a uniform system" (Meadows, 2008, p. 3). Diversity similarly facilitates the adaptive capacity of a system (Norberg and Cumming, 2008) while simultaneously reducing the rigidity of the system (Rotmans et al., 2010, l. 4124). It does this by maintaining a store of options, functions and responses to various changes and shocks. For this reason, diversity is most useful during times of change and instability, when the existence of the system is being threatened (Norberg and Cumming, 2008, p. 12). It is because of diversity that the economic system, for example, is adaptable which makes it "capable of continuous performances in the face of changing, uncertain circumstances" (Bertolini, 2010, l. 2086).

While diversity creates stability, too much diversity within a system can lead to a breakdown in resilience (Page, 2011). "During times of stability, diversity can become a burden on the system because maintenance of system components requires energy, and many components in a diverse system may be relatively inefficient or even unnecessary" (Norberg and Cumming, 2008, p. 12). For this reason, many CAS go through cycles of increasing and decreasing diversity as the stability of the system changes. These cycles "may cause a loss of function and a systemic reorganization, possibility leading to a new configuration of the system"[16] (Norberg and Cumming, 2008, pp. 12–13).

2.6.8. Redundancy

Redundancy implies duplication or back-ups of that part or function of the system. If one part collapses, there is another that will take its place and perform the same function (Fleischhauer, 2008, p. 277). Redundancy is the "extent to which different system elements can satisfy the same functional requirements; a diversity of pathways (or potential for creating a diversity of pathways) for achieving the same goal" (United Nations and Asian Development Bank, 2012, p. 90). Redundancy can take shape in a variety of different forms, including connectivity to other systems to substitute for broken or missing links.

Page (2011, p. 228) describes two types of redundancies, namely pure redundancy (or modularity as described by Ahern (2011, p. 342)) and degeneracy. Pure redundancy refers to having numerous duplicates (carbon copies) of the same part; for example, having several spare light bulbs so that a defunct bulb can be replaced with another that is exactly the same. In an urban system, this could be spare municipal busses, or a back-up electricity supply system, for example local generators, to provide power in the event of a system-wide failure. It is commonly used in computer networks to safeguard data. Degeneracy on the other hand can be described as structures or elements that can perform the same function but are physically different (Page, 2011, p. 54); for example, pen and paper,

[16] See Chapter 6 section 6.2 on the adaptive cycle for more on the cycles of change that CAS go though.

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a computer, a cell phone, tablet or a white board can all be used to record information or make notes of some kind. In a socio-economic system, redundancy could include different forms of education such as state, private or religious schools, colleges or universities, or private tutors or home schooling.

2.6.9. Resilience

"**Resilience** is fundamentally a system property. It refers to the magnitude of change or disturbance that a system can experience without shifting into an alternate state that has different structural and functional properties" (Resilience Alliance, 2010, p. 5 [Resilience Alliance's bold]). In short, resilience refers to the system's ability to absorb disturbances, both short and sudden shocks, as well as slow long pulses while adapting to changes within its environment.

According to Davoudi et al. (2012), Folke (2006) and Gunderson and Holling (2001), there are three main types of resilience, namely engineering resilience, ecological resilience and evolutionary or social–ecological resilience, each of which has been summarised in Table 5.

Table 5: Concepts of resilience

Resilience Concept	Definition
Engineering Resilience	Engineering Resilience refers to the system's ability to absorb and 'bounce back' after a shock and return to equilibrium while still maintaining the same functional and structural identity. The higher the resilience faster the system will return to equilibrium (Davoudi et al., 2012; Folke, 2006).
Ecological Resilience	This definition of resilience acknowledges that a system may have several stable states or attractors to which it could move to. Here the emphasis is on the system's ability to maintain its functions and processes while undergoing internal or external stress and or pressure by either resisting, adapting or reorganising itself in order to build its adaptive capacity (Davoudi et al., 2012; Folke, 2006; Marshall and Schuttenberg, 2006).
Evolutionary/ social–ecological Resilience	"Evolutionary resilience challenges the whole idea of equilibrium and advocates that the very nature of systems may change over time with or without an external disturbance" (Davoudi et al., 2012, p. 302). Here the emphasis is on the fact that system may not go back to a previous stable state but will rather evolve or adapt to a new stable state in response to stress (Davoudi et al., 2012; Folke, 2006; Gunderson and Holling, 2001).

From Table 5 it can be argued that resilience is more than just the system's ability to recover from shock and return to a stable state (Folke, 2006). It is also about the system's ability to adapt and reorganise itself to maintain certain structures, functions and processes (Folke, 2006; Folke et al., 2004; Gunderson and Holling, 2001; Marshall and Schuttenberg, 2006; Norberg and Cumming, 2008), as well as the ability to then transform itself and move into a new state if necessary (Davoudi et al., 2012; Gunderson and Holling, 2001; Walker et al., 2004).

Resilience forms in complex adaptive systems as a result of several system processes and properties working together to allow the system to persist. Among these are diversity (Ahern, 2011; Gunderson and Holling, 2001; Page, 2011); redundancy (Ahern, 2011; Fleischhauer, 2008; Page, 2011; United Nations and Asian Development Bank, 2012); adaptive capacity (Folke, 2006; Gunderson et al., 2008; Hjorth and Bagheri, 2006; Lang, 2012); system structure (Geyer and Rihani, 2010; Meadows, 2008;

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Salat and Bourdic, 2012b) and buffers or stores (Fleischhauer, 2008; Gunderson and Holling, 2001; Resilience Alliance, 2010; United Nations and Asian Development Bank, 2012).

2.6.10. Co-evolution

Complex adaptive systems are open to and interact with their environment (Cilliers, 1998; Gerrits and Teisman, 2010; Holland, 2012; Human and Cilliers, 2013). This means although a system may have a boundary[17], be it naturally forming or human delimited, it will still interact with its environment and vice versa (see Figure 17 for an example). Often it is difficult to differentiate between the system and its environment (Cilliers, 2005a, 1998; Human and Cilliers, 2013). The differentiation comes in the form of how the system is defined, thereby setting boundaries to the system from a particular point of view, a process also called framing (Cilliers, 2005a, 1998; Human and Cilliers, 2013). By delimiting boundaries to the system, some aspects of the system are negated. It is because of the open nature of systems that we can observe the process of co-evolution.

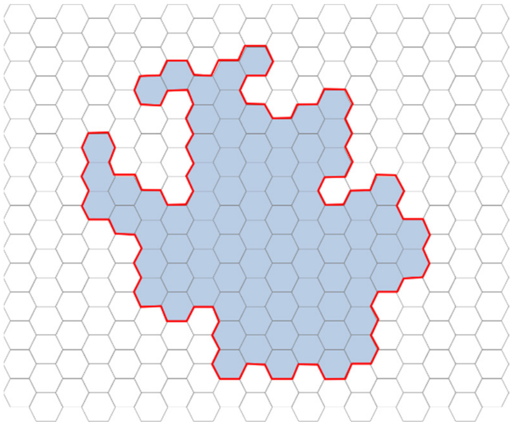

Figure 17: A system (blue cells) with its boundary (red) interacting with its environment (white cells).

Co-evolution differs from evolution in that the mutation or adaption viewed in the system can be explained by the external pressure of the environment on the system. Co-evolution highlights the fact that there is actually a reciprocal relationship between the system and it environment. The mutation or adaption in the system, that was a result of the pressure from the environment, in turn places its own pressure on the environment. In this way any change in the system will have an effect on the environment, while any change in the environment will have an effect on the system (Gerrits and Teisman, 2010).

The process is further explained in Figure 18 (and shown in Figure 19, where a simplified process of co-evolution has been illustrated). Starting at (1) where the environment interacts with the system which (2) results in the system adapting. The system then interacts (3) with its environment which (4) then causes an adaption in the environment. (5) The process then repeats itself in an endless loop.

Through this process of constant adaption in response to changes in the system's environment, the system often becomes more specialised and dependent on its environment (Holland, 2012, p. 19; Miller and Page, 2007, p. 237). However, this process is very slow and the initial process of co-evolution can lower the system's fitness landscape[18], which allows the system to establish effective

[17] See section **4.2** for more on boundaries

[18] Fitness landscape refers to how well adapted or specialised a system is to a problem or an environment. The more specialised the system is to a particular environment the 'fitter' the system is and the more efficiently it can operate within that environment (Lansing and Kremer, 1993, p. 104).

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structures that later make it possible for it to evolve at a much faster rate (Miller and Page, 2007, p. 237). This evolution then tends to allow the system to become more specialised for its particular environment as it co-evolves with its environment (Holland, 2012, p. 19; Miller and Page, 2007, p. 237).

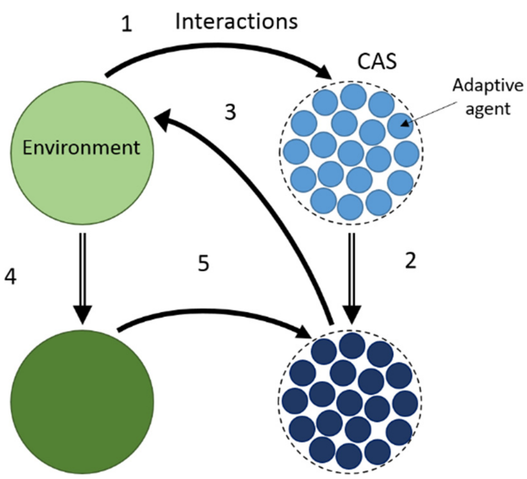

Figure 18: A simplified process of co-evolution

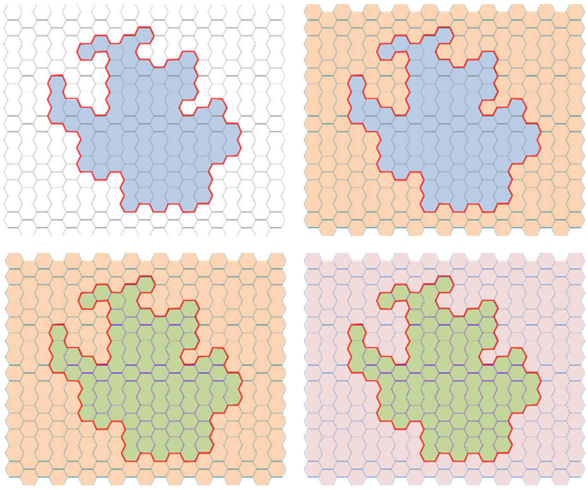

Figure 19: (Top left) A system (blue) within its environment (white). (Top right) Through interaction with the system, and its own internal dynamics, the environment has adapted. (Bottom left). The change in the environment has driven a response within the system

2.6.11. Properties working together

To summarise: CAS are made up of a large number of diverse and highly connected agents. These agents follow relatively simple rules that govern their non-linear interactions (Richardson, 2005a, p. 619). Changes or adaption of the rules that individual agents follow as they respond to changes by other agents and the environment, can lead to a system-wide adaption designed to allow the system to respond to, and deal with, current and future environments.

Capra (1984, p. 276) proposes that "Systemic properties are destroyed when a system is dissected, either physically or theoretically, into isolated elements. Although we can always discern individual parts in any system, the nature of the whole is always different from the mere sum of its parts". It is for this reason that we look at the whole and not just the part. Furthermore, by studying the interactions and not the individual parts of the system, we may be able to understand the structure and dynamics of change within complex adaptive systems (Alberti and Marzluff, 2004, p. 242; Sanders, 2008, p. 275), as well as how, through the various and numerous interactions, the system self-organises (Allen, 2005; Lansing, 2003; Portugali, 1997). Through the process of self-organisation, agents can also aggregate together to form higher order agents, which then follow their own set of rules. Aggregation of agents creates natural self-driven (bottom up) hierarchical structures and processes. These structures tend to form naturally within the system (Holland, 1998, pp. 9 – 10). The persistence of these structures and processes of self-organisation over time leads to a global, system wide, pattern or behaviour that emerges on its own (du Plessis, 2009; Holland, 1998; Johnson, 2002; Miller and Page, 2007). Figure 20 further illustrates how these processes work together by illustrating

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that, as time moves (left to right), the interaction of the agents self-organise to create not only higher level aggregate agents that have different emergent properties but also through these interactions the agents adapt their rules which allows the system to evolve over time.

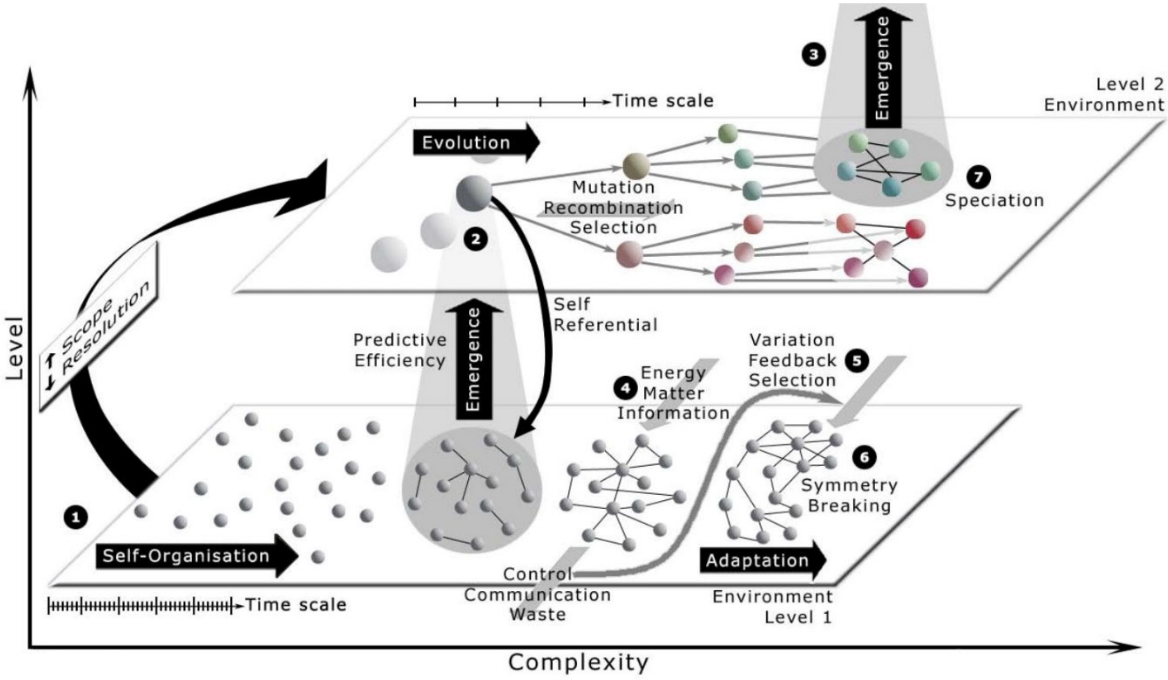

Figure 20: Demonstration of processes at within complex adaptive systems. Adapted from Ryan (2007, p 114)

2.7. Complexity and the changing city

What makes complexity theory so useful for the study of cities? To answer this Portugali (2011, pp. 95–96) argues that complexity theories of cities have provided a solid mathematical and theoretical basis to many of the ideas presented by authors such as Jacobs (1961) and Alexander (1966). Complexity theories of cities not only provide scientific evidence for some theories. They also bring together and help to explain other theories and observations of urban phenomena. In essence, they give “a single and sound theoretical basis to a variety of urban phenomena and properties that so far were perceived as independent of each other and thus interpreted by reference to different theoretical bases” (Portugali, 2011, p. 96). In addition to supporting and bringing together many theories, complexity theories of cities have provided new insights to the understanding of cities that echo the fundamental properties of complex systems (Portugali, 2011, p. 96).

To illustrate this point, the first part of the section to follow will begin with a description of how cities can be seen as CAS. This will be done by showing how some of the properties of a CAS present themselves within the urban context. The second aspect that will be presented is how cities are not only CAS but also social-ecological systems. This aspect brings in social-ecological systems theory (SES) of complex systems which will be used later in this study as a theoretical basis to help describe change in the CAS and, in this case, the city. The final part of this section will then look at how urban change is understood from the perspective of the city as a CAS.

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2.7.1. Cities as complex adaptive systems

Understanding that cities are complex adaptive systems can assist urban planners not only better to understand and deal with the growing complexities of cities but also allow them to develop better strategies to manage these complex adaptive systems (Cilliers, 2008, p. 40; de Roo et al., 2012, p. 241). For this to take place, how cities are in fact CAS must be understood.

Rief (1973, p. 26) argues that a "careful analysis of the structure of a city demonstrates that it is not possible to study any of its parts in isolation, because they are strongly related to other elements of the city structure" and, in order to study one part, we must consider the other related parts. The argument Rief (1973) makes about the need to look further afield when studying a part of the city links strongly to the idea that a complex system is open and consists of more than the sum of its individual parts; that to understand a part of the whole, the broader context in which the particular part of the system finds itself must first be understood. Additionally, the interactions between the parts must be understood. With this Rief (1973) begins to introduce why cities can and should be seen as CAS.

The idea that cities are systems is not new and has been around for as long as systems thinking has been with us (du Plessis, 2008a, p. 85). According to many authors (see Ahern (2011), Barthelemy et al. (2013), Batty (2008, 2007), de Roo et al. (2012), de Roo and Silva (2010), Du Plessis (2008b), Geyer and Rihani (2010), Holland (1998), Innes and Booher (2010), Nel (2009), Portugali (2011), Salat and Bourdic (2012b) and Sanders (2008)) cities are complex adaptive systems. As will be described below, cities display the properties of complex adaptive systems and as such can be said to be complex adaptive systems in their own right.

Cities are comprised of a large and diverse number of agents and aggregate agents (i.e. a single person, household, firm or government) whose interactions lead to behaviour that can be difficult to understand and predict (Barthelemy et al., 2013, p. 1; Rounsevell et al., 2011, p. 260). They demonstrate non-linear behaviour and are far from equilibrium (Wilson, 2010, p. 25). For example, the "local action and/or behaviour of a single 'small' urban agent (for example, a single person) might affect the city much more strongly that the actions of a big strong agent such as the city planning team" (Portugali et al., 2012, para. 1223). Portugali et al. (2012) go on to highlight that, for this reason, the importance and role of individuals in shaping the city should not and cannot be ignored.

Additionally, because cities are non-linear systems, they are sensitive to initial or starting conditions (Geyer and Rihani, 2010, p. 44; Nel, 2009, p. 26; Wilson, 2010, p. 25). What this means is that the current state of the city is a result of its past, and its future path is dependent on the present (see section **5.2** for more on the importance of a system's history). According to Wilson (2010, p. 25), initial conditions can be thought of as the "variables that represent the slowly changing (infra) structures of the systems of interest and hence determine the possible paths of future development, something that can be thought of as a 'cone of possible development'".

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Although cities may at times seem chaotic or disorganised, this is not so. Rather, they are Class IV systems that lie between order and chaos. It is due to the non-linearity of the interactions that complex systems and cities have the ability to self-organise (Nel, 2009, p. 25).

The ability to self-organise is perhaps one of the city's most defining characteristics. Self-organisation within the city can be seen as a city's ability to spontaneously coordinate itself without any top-down direction. This occurs as a result of each agent (person, household or company) making decisions based on interactions with other agents and the local environment (Helbing, 2009, p. 425; Johnson, 2002, pp. 87–100; Pulselli et al., 2006, p. 127). These decisions then result in events and patterns such as "traffic, crowds, organizations, companies, or production plants" (Helbing, 2009, p. 425). These patterns can extend beyond the local and lead to a more global behaviour (Pulselli et al., 2006, p. 127).

This global behaviour is called emergence. Emergence is concerned with the macro behaviour of the system generated through the micro level interactions of elements on the smaller, local, level. This behaviour cannot be predicted simply from the knowledge of the individual elements (J. Hillier, 2012, p. 1303). Portugali et al. (2012, l. 1223) support this by saying, for a city, emergence "means that the local interactions between urban agents often give rise to properties that exist only at the global scale of a city". Examples of emergence within the city include the natural formation of spatial segregation within the city (Batty, 2007, pp. 51–57; Portugali et al., 2012, l. 1225), the creation of (sub)cultural groups (Portugali, 1997, p. 374), the emergence of suburbia and sprawl (Johnson, 2002, pp. 88–100) and the creation of organisations (Pulselli et al., 2006, p. 129), to name just a few examples.

Pulselli et al. (2006, p. 127) suggest that "In a city or social system, the configuration of interactions between parts, such as individuals, and between the parts and the whole, is an expression of the system's organization, achieved by processes of adaptation and selection". Next to self-organisation, adaption is perhaps one of the most important features of a city. Adaption occurs at the lowest level, that of the agent (Holland, 1996, p. 10). The system itself does not adapt, it is rather agents of the system that adapt by altering their behaviour (Holland, 1996, p. 10; Page, 2011, p. 25). However, these small adaptions by individual agents can lead to a sub-system or even system-wide adaption(Page, 2011, p. 25). If we apply this thinking to cities, an easy example can be changes in land use (zoning) or

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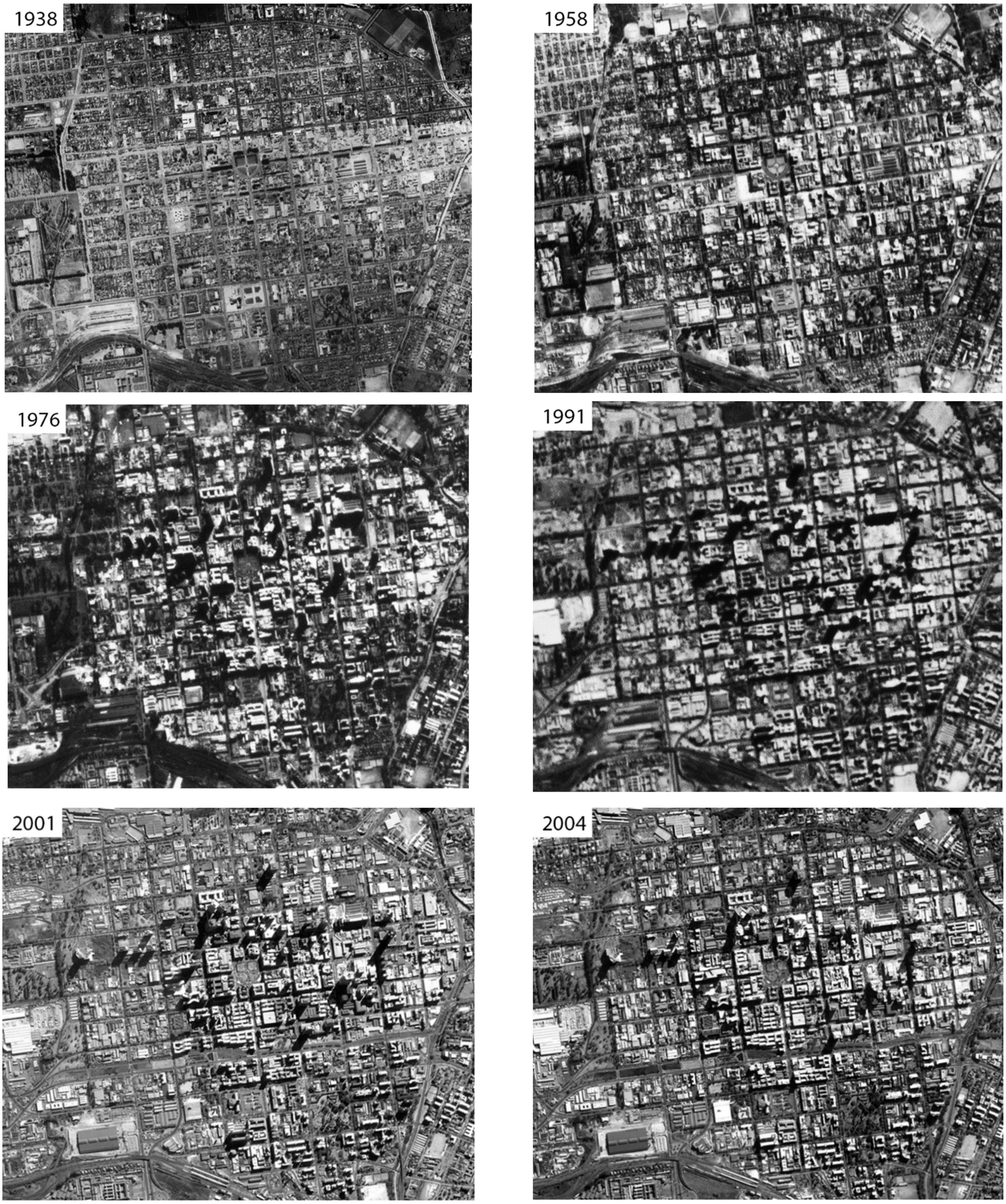

Figure 21: Land use and building changes in Tshwane's CBD from 1938 - 2004. Image sources: 1938, 1958, 1976, 1991 National Geo-spatial Information (NGI) and 2001 and 2004 Google Earth

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changes in buildings in an area over time, Figure 21[19] illustrates the latter. Figure 21 shows several aerial photos of the central business district (CBD) of Tshwane (formally Pretoria) and how it has changed over 66 years. From the images, we can see the general trend is that the buildings in the CBD have gone from predominantly small one or two story buildings, with several buildings per block (in 1938) to much larger multi-story buildings, with fewer buildings per block (in 2004). In addition, we also see how, due to increasing use of cars and the demand for greater mobility, the roads have been widened (bottom left of 1991 - 2001) or how an entire section of the city has been altered between 1976 -1991 (top left). Over the 66 year period, the cascade of individual, relatively small, changes to buildings have resulted in a complete transformation or system- wide adaption of the CBD. In this way the city, through its adaptions, can be seen to evolve over time.

Cities are made up of many different types of natural forming, interdependent hierarchies of systems that are often viewed through their various sub-systems. For example, “transportation, retail, health, welfare, crime, finance, water, political , refuse disposal” can be seen as sub-systems of the larger urban system (Johnson, 2012, l. 3585). These sub-systems interact and enable each other to function, i.e. the transportation system, by moving people from their homes to their places of work, can enable the economic system. Additionally, these sub-systems also have their own interacting sub-systems (see Figure 22), i.e. people making use of a multimodal transportation system that is comprised of a train sub-system, bus sub-system and pedestrian sub-system to move around the city (Johnson, 2012, l. 3590). Batty (2014, p. 770) reasons that natural hierarchies form within the city in terms of “different subcenters or clusters across many scales, from the entire city to neighborhoods, organized around key economic functions”.

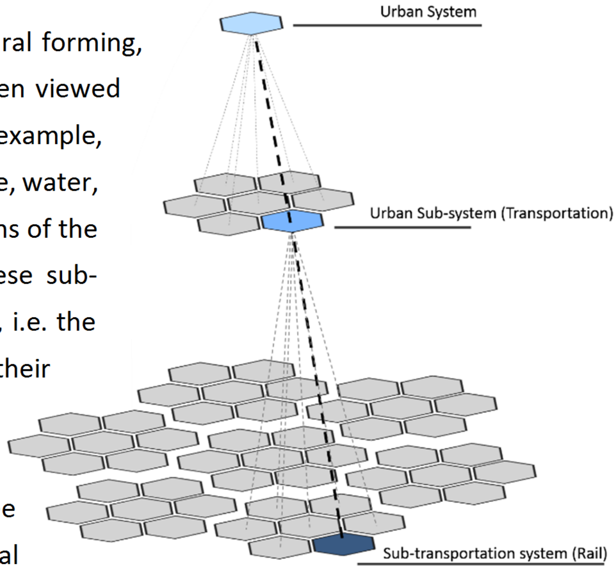

Figure 22: An example of one way in which a city can be seen as a series of multilevel sub-systems.

One of the ways that these hierarchies can be seen and studied within the urban system is by examining cities with the ‘rank-size rule’, also called Zipf’s Law (Barabási and Bonabeau, 2003; Batty, 2014, 2008, 2007, p. 35; Crumley, 1995; Jiang, 2009, 2007; Pumain, 2012, p. 2179; Salat and Bourdic, 2011). Zipf’s Law suggests that “the size of cities P_r (and their frequency) scales according to the size of the largest city P as $P_1 \approx P_r/r$, where r is the rank of the city by size in descending order from largest city of rank r = 1” (Batty, 2007, p. 35). In other words, Zipf’s Law argues if we rank cities from largest to smallest by population, for example, we should find that there are very few large cities with

[19] The changes can be better identified by viewing the animated version of the Figure 21 at: http://fc06.deviantart.net/fs70/f/2015/042/1/2/pta_1938_2004_by_cloaked_lotus-d8hjzo8.gif

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enormous populations, but as the size of the city's population decreases, there should be a proportional increase in the number (frequency) of small cities (Batty, 2014, 2007, p. 35; Gabaix, 1999, p. 741; Salat and Bourdic, 2011, p. 1194). This power law is also consistent with Christaller's central place theory (Batty, 2007, p. 35; Salat and Bourdic, 2011, p. 1194).

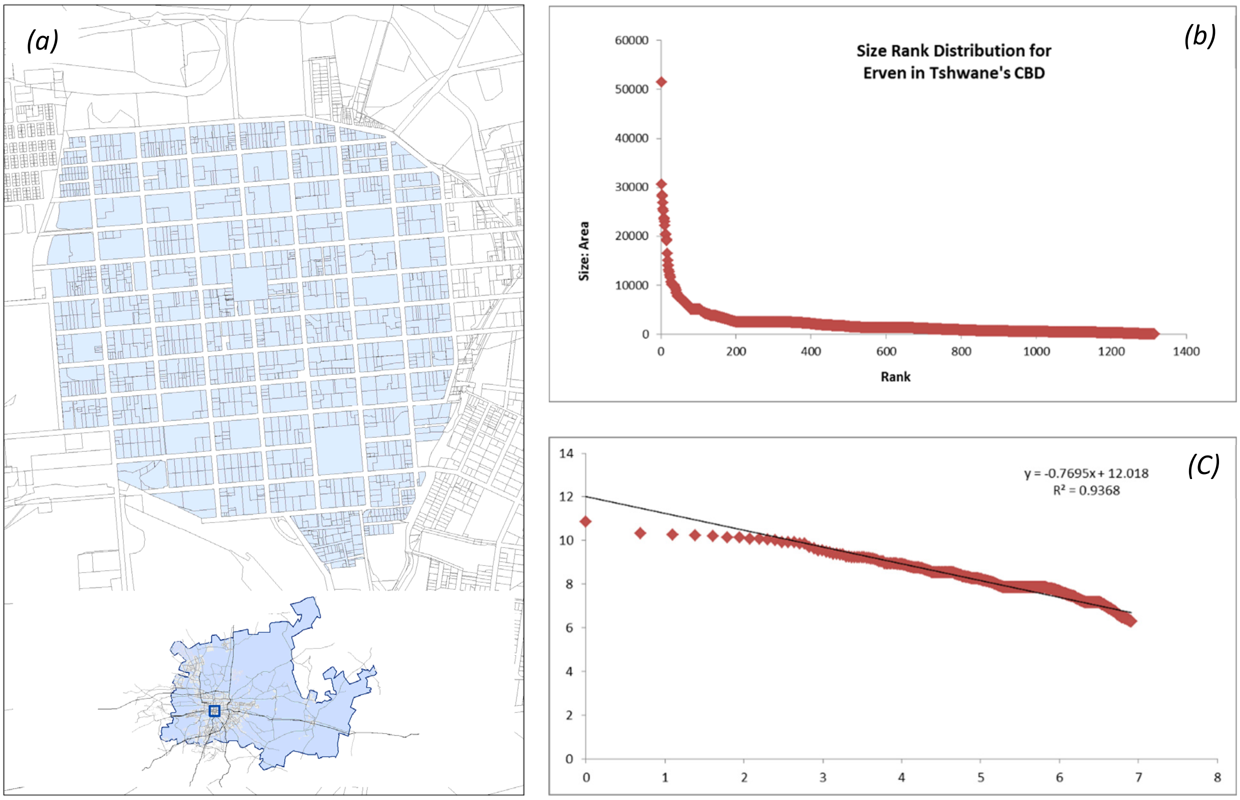

Figure 23: (Left) Central Business district of the City of Tshwane indicating the erven (blue) used. (Right Top) Rank scale distribution of erven for the study area. (Right Bottom) The Log Size verses the Log Rank of the erven.

In Figure 23, an example has been presented of how Zipf's Law can be applied in an alternative way by using the same methodology described by Batty (2007, p. 35) and Gaxaix (1999, pp. 739–740). The example shows a visualisation of land parcels found within the CBD of Tshwane in Figure 23(a). The land parcels were then ranked according to their size/area as seen in Figure 23(b), after which the Log for the rank and size was determined, as described in Figure 23(c). The result of this was $R^2 = 0.9368$. As R^2 is close to 1 it indicates that Zipf's Law is applicable in terms of the size and rank (frequency) of land parcels in the CBD, telling us that there is a natural hierarchy in terms of land parcels in the area.

Additionally, some authors have begun exploring alternative ways that Zipf's Law may be used to identify natural hierarchies within the city. These examples include temporal shifts (Batty, 2014), morphology (including densities and spatial distribution within cities (Batty, 2009, 2008, 2007; Bourdic et al., 2012; Salat, 2011; Salat and Bourdic, 2012b, 2011), income distribution of companies (Okuyama et al., 1999), scaling in public transport networks (Von Ferber et al., 2005) and urban supply networks (Kühnert et al., 2006).

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While cities contain natural hierarchies, they are also very diverse. To help illustrate the fact that cities are enormously diverse, Jane Jacobs (1961, p. 187) uses the example of a classified telephone directory which "tell us the greatest single fact about cities: the immense numbers of parts that make up a city, and the immense diversity of those parts. Diversity is natural to big cities". Jacobs' (1961, p. 187) argument is that the city is not only made up of an extraordinary number of agents (people and companies) but, within this large number of agents, there is an equal degree of diversity.

Diversity within the city manifests in a wide variety of ways. These include, but are not limited to, building and housing types (Fainstein, 2005, p. 4); land uses (Jacobs, 1961, p. 188); population, including racial and cultural groups (Allen, 2012, l. 1668; Talen, 2008, p. 17, 2006, p. 235); physical form and morphology, including densities (Pumain, 2012, l. 1189) and economic diversity (Duranton and Puga, 2000, p. 534) to name but a few.

Diversity has many roles for the effective functioning of a CAS and a city. One of these is that diversity helps to improve the level of self-organisation within the city by allowing for a variety of possibilities. I In doing so, it allows for new opportunities for change (de Roo and Rauws, 2012, l. 4843). In the same way, diversity also enables resilience by reducing the rigidity within the system and creating flexibility (Rotmans et al., 2012, l. 4127).

Salat and Bourdic (2012a, 2012b) provide an example of how diversity increases resilience within the city. They use the transportation network as an example. Diversity in this context can be seen in two ways, the first being the variety of types of transport (i.e. rail, bus, tram and car), the second being the diversity of possible routes within the network. Important to note in this case is that some of the possible types of transport can also use the same network (i.e. bus and car using the road network), if not always to the same extent. For this example, Salat and Bourdic use the road network. Salat and Bourdic (2012a, 2012b) argue that a road network that has a strict hierarchy and few connections between the roads will be more variable and less resilient.

The example in Figure 24 illustrates what Salat and Bourdic (2012a, 2012b) mean. Figure 24 shows two road networks (a1) and (a1). Consider these two networks and imagine that one has to travel from point A to point B in both (red dots in Figure 24). In a normal trip, there are several possible routes, which means that there should be no problems getting from point A to B in each of the neighbourhoods. But if, for some unknown reason, a part of the road that would normally be used is closed (Figure 24 (a2) and (b2), section indicated in blue), we find that for (a2) the number of possible routes decreases, while the length of the route increases significantly. In (b2) this is not the case, as the network is far more open and has a larger variety of alternative routes available. If we consider that there are other road users in these two neighbourhoods, then the scenario presented in Figure 24 (a2) and (b2) becomes an issue, as the vehicles that would have travelled in the closed section of road now have to find alternative routes, which adds more pressure on the existing network to handle the increased traffic.

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What the example presented above illustrates, is how diversity can create redundancy, which in turn, can help create resilience. In the case of the example, the redundancy is in the form of a diversity of possible routes that allow for flexibility and choice, thereby increasing the system's ability to manage disruptions. In the same way, having multiple modes of transport can further increase the diversity and redundancy of the transportation network which will add to the transportation system's resilience (Salat and Bourdic, 2012a, p. 32).

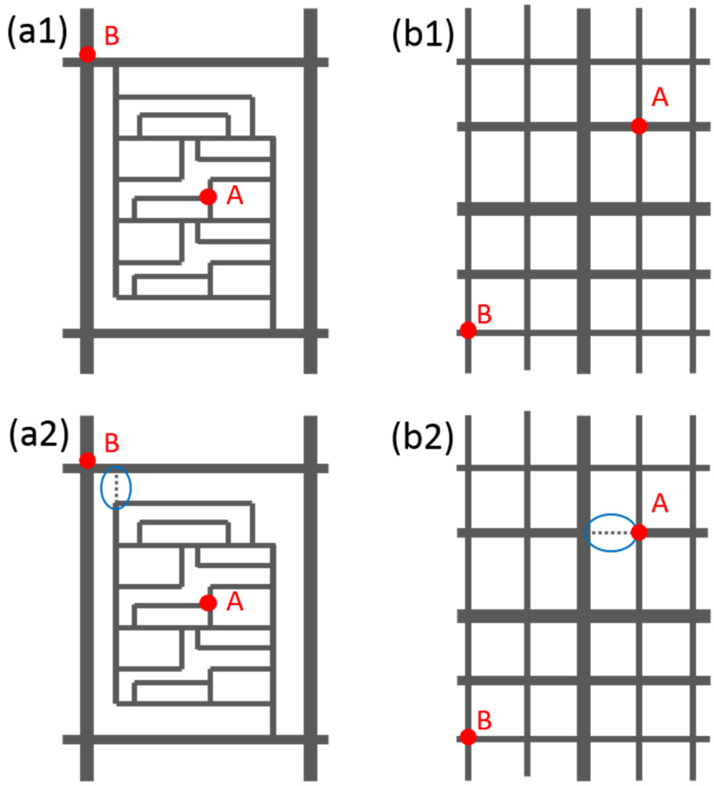

Figure 24: Road networks for two neighbourhoods. (Left) (a1) and (a2) shows a closed road network with a strict road hierarchy and few redundancies while (Right) (b1) and (b2) show an open grid road network.

From the discussion above, it is clear that cities are indeed complex adaptive systems as they have all of the properties of any CAS. They are made of an extraordinarily large and diverse number of self-organising agents that interact with each other in a non-linear way. Through the interactions, the agents respond to changes in their environment and, in doing so, adapt their internal rules. When done by most of the agents, this can lead to a system/city wide adaption. The resultant system wide adaption can be seen as an emergent behaviour of the system as it is a result of the system's ability to self-organise. Furthermore, naturally forming hierarchies also emerge within cities. Zipf's Law is a tool that can be used to identify and describe such hierarchies.

2.7.2. How are cities studied as CAS?

Traditionally theories of cities have viewed the city as a static entity with little emphasis on their dynamics. These theories viewed the city as close to equilibrium, where the whole *is* merely the sum of its parts (Batty, 2007, p. 109). However, with the rise of systems and complexity theory, we know that cities are in fact complex dynamic systems that are far from equilibrium and whose global behaviour emerges, over time, from the bottom-up.

The above discussion described what CAS are and their properties. The question now is how to study them? In short, there is no one specific way to study cities just as there is no one specific way to study CAS in general, let alone the study of cities as CAS. Holland (2006) demonstrates this point by providing

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several examples of techniques used for studying complex systems from various fields of study20. One of the more popular ways CAS are studied is through the use of models. Models can be seen as a concept, a law, or any description of a phenomenon that aims to represent or reflect the real world (Cilliers, 2001, p. 2; Miller and Page, 2007, pp. 36–37). They allow us to understand something about whatever is being modelled (Holland, 1998, p. 33). Many models of CAS are mathematical or computer based. These include, but are not limited to, agent based models (Batty, 2007; Epstein and Axtell, 1996; Miller and Page, 2007; Resnick, 1994; Shan and Yang, 2008), cellular automata (Batty, 2007; Cilliers, 1998; Epstein and Axtell, 1996; "John Conway's Game of Life," n.d.; O'Sullivan, 2000; Portugali, 2011), and network models (Barabási and Bonabeau, 2003; Barthélemy, 2011; Batty, 2009; Blanchard and Volchenkov, 2009; Boccaletti et al., 2006; Frasco et al., 2014; Hein et al., 2006; Neal, 2013; Skjeltorp and Belushkin, 2006; Solé, 2011).

According to Holland (2006, p. 3), the similarities between the various approaches suggests that cross-disciplinary approaches to studying CAS have considerable value. Each technique is the result of extensive research and comparing the relevant parts of each technique to the application of studying CAS, possible dead ends found in one approach can be avoided in another (Holland, 2006, p. 3). Although not against modelling of CAS, Cilliers (1998, p. 58) cautions that to have accurate models, any models of CAS "will have to be as complex as the systems themselves. They will also have to emulate these systems' capacity to encode and remember information pertaining to their environment and how to cope with that environment", making this a virtually impossible task.

In response to this argument, Miller and Page (2007, p. 35) remind us that "Effective models require a real world that has enough structure so that some of the details can be ignored". Miller and Page (2007, pp. 35–40) argue that models require us to ignore some aspects of the real world in order to understand the underlying structures of what is being modelled. Batty (2007, p. 109) adds to this by saying the purpose of modelling "is not to provide accurate descriptions of urban growth or to provide predictive models for urban planning; it is to strip the processes of city growth to their bare essentials, and to thus uncover the basic mechanisms at work". Batty's rationale is if we better understand these processes, then we are better able to comprehend the limits of our global interventions, whose processes are essentially based on local behaviour (Batty, 2007, p. 109).

As the discussion above highlights, there is an ongoing debate around the use of models in understanding the city. But from the point of view of understanding change, models are very useful as they allow us to ask many different questions and create various scenarios. From the review of the literature, most of the studies aimed at understanding cities as complex systems have focussed on understanding the self-organising processes within cities, through the use of computer models (see Batty (2014, 2009, 2008, 2007), Batty and Xie (1999), Batty and Stanilov (2010), Irwinet al. (2009), Pumain et al. (2006) and Wilson (2010), Wray et al. (2013) for some examples). Roggema (2012, p.

[20] The techniques Holland (2006, pp. 2–3) names are Control Theory, Economics, Biological Cells and Games (Game Theory)

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102) provides a cautionary note about computer modelling, arguing that although modelling may help us to understand the self-organisation of the city, these models often lack the "tools to influence the performance of the city". He argues that cities are mainly seen as objects on which to perform analysis and then model, and that these models are hardly ever used to inform planning decisions.

There are many models available to us and, according to Batty (2007, p. 152), it is easy to describe changes that have taken place after the fact, it is "almost impossible to develop convincing theories that enable us to make informed predictions" (Batty, 2007, p. 152). This is due to the fact that, as expressed by Cilliers (1998, p. 58), any model will have to be as complex as the system being modelled. It is for this reason that many models tend to have a specified goal, to simulate a particular sub-system. An example of this can be seen in the work of Wegener et al. (1994, p. 23) who compare twelve different urban models (see Table 6). Each of these looks only at a particular sub-system or series of sub-systems (the sub-systems being studied are: networks, goods transport, employment, workplaces, land use, housing, population and travel); and the theory on which the modelling has been based as well as what particular goal/policy was held in mind for the model.

Table 6: Summary of comparison of twelve urban models. Adapted from Wegener (1994, p. 23)

Model	Sub-systems modelled	Model theory	Policies modelled
POLIS	Employment Population Housing Land use Travel	Random utility locational surplus	Land-use regulations Transportation improvements
CUFM	Population Land use	Location rule	Land-use regulations Environmental policies Public facilities Transportation improvements
BOYCE	Employment Population Networks Travel	Random utility General equilibrium	Transportation improvements
KIM	Employment Population Networks Goods transport Travel	Random utility Bid-rent General equilibrium Input-output	Transportation improvements
ITLUP	Employment Population Land use Networks Travel	Random utility Network equilibrium	And-use regulations Transportation improvements
HUDS	Employment Population Housing	Bid-rent	Housing programs
TRANUS	All sub-systems	Random utility bid-rent network equilibrium land-use equilibrium	Land-use regulations transportation improvements transportation-cost changes
5-LUT	Population networks housing	Random utility bid-rent general equilibrium	Transportation improvements

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Model	Sub-systems modelled	Model theory	Policies modelled
LILT	All sub-systems except goods transport	Random utility network equilibrium land-use equilibrium	And-use regulations transportation improvements travel-cost changes
MEPLAN	All sub-systems	Random utility Network equilibrium Land-use equilibrium	Land-use regulations Transportation improvements Transportation-cost changes
IRPUD	All sub-systems except goods transport	Random utility network equilibrium land-use equilibrium	And-use regulations Housing programs Transportation improvements Travel-cost changes
RURBAN	Employment population housing land use	Random utility bid-rent general equilibrium	Land-use regulations transportation improvements

Table 6 highlights some available models to help understand the urban system, or a part thereof. One cannot neglect the theories on which many models have been based. Among the many theories of cities available are included D*issipative Cities* (Allen and Sanglier, 1981; Nicolis and Prigogine, 1977; Schieve and Allen, 2014), *Synergetic Cities* (Daffertshofer et al., 2001; Haken, 1983; Portugali and Haken, 1995) and *Sandpile cities*, also known as *Self-organised criticality* (Bak, 1997, 1990; Batty and Xie, 1999). What all of these theories all have in common is that they attribute the phenomenon of urban growth and change to the process of self-organisation.

While models can be seen as useful laboratories for the study of the city, there has also been a strong critique against them. Among the strongest being from Sayer (1976)[21], whose criticism was aimed primarily against urban models "rooted in mathematical formalism, static equilibrium and urban economics" (O'Sullivan, 2004, p. 288). O'Sullivan (2004, p. 288) indicates that, while most models do still have a strong bias in favour of economics, our attention should rather be on the theories represented in the models, and not the models themselves. Instead O'Sullivan (2004, p. 291) suggests that we should see "complex geographical models as extensions of thought experiments, where the necessary and contingent implications of theories can be examined". Rotmans (2006, p. 160) adds that, among the many critiques of urban planning tools under which models and modelling fall, is the fact that they are frequently too complex and data intensive, and often cannot handle qualitative data.

The above discussion highlighted that the theories on which models are built should be the focus of study not the models themselves. Additionally, models cannot effectively use qualitative data. It is for these two reasons that part of the framework to be described in later chapters, was developed.

2.7.3. Looking at urban change

When it comes to understanding change in the city, Batty (2007, pp. 21–24) writes that there are five main drivers of change. These drivers are: randomness; historical accident; physical determinism; natural advantage and comparative advantage. *Randomness*, as Batty (2007, p. 21) calls it, refers to

[21] Many of Sayer's (1976) critiques have been addressed by modern theories and models over the past forty years (O'Sullivan, 2004, p. 288).

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the fact that some "part of urban change might be determined by whim". What Batty means by this is decisions that affect urban change cannot always be predicted and can happen seemingly at random. This randomness can therefore be seen as 'noise' in the decision-making process.

The second of the drivers of change is *historical accident* and refers to the fact that a decision made in the past can have long-term consequences on the future growth of the city, essentially setting it on a particular path that is it difficult to change. This is also called path dependency (Batty, 2007; Beinhocker, 2006; Geyer and Rihani, 2010; Levin, 1998; Roggema, 2012) and is discussed in more detail in chapter 5.

While historical accidents play a role in determining urban change, *physical determinism* also plays an important part (Batty, 2007, p. 22) and refers to areas where it is difficult or impossible to develop, i.e. a river or a mountain. These barriers to development may be overcome through developments in technology, for example. However, because of the initial physical environment in which the city may have been set, it many also be a particular development path that is now difficult to change.

Coupled to physical determinism are *natural advantages*. While the physical landscape may hinder development in some ways, it can also lead to the city being located in an area where natural resources can be exploited in such a way as to determine the decisions to locate nearby for economic gain (Batty, 2007, p. 23). Examples include the location of a river, harbour and minerals (i.e. gold or coal).

Finally, the last driver of urban change that Batty (2007, p. 23) describes is *comparative advantage*, which can be roughly defined in this context as the ability of a city to specialise more in one aspect (i.e. to provide access to a particular service, e.g. parks) than in any other aspect or service (Batty, 2007, p. 23; Mohr and Fourie, 2008, pp. 372–373). Batty (2007, p. 23) notes that this driver is the "most problematic of the five drivers of change: the first four can be traced to whimsical factors or to physically determined elements. The fifth is a constantly shifting nexus as the city develops".

While Batty has identified some of the main drivers of urban change, Wegener et al. (1986) presents another aspect that will have to be considered, i.e. not all processes of change take place at the same time or have the same impact on or response by the system. Wegener et al. (1986), using the work done by Snickars et al (1982), make the distinction between slow, medium and fast processes of change. A summary of their work has been presented in Table 7. In Table 7, going from left to right, Wegener et al. (1986, pp. 3–7) describe the speed of the process (level 1 being slow and 3 being fast); the process creating the change (Change Process); what is affected by the change (Stock Affected); how long the system typically takes before it starts to respond to the change (Response Time); how long the system takes from when it first starts responding to a change to when it stops (Response Duration); the response level refers to the duration of the response and "indicates the normal rate of change associated with the process in relation to the magnitude of the affected stock. If the life-cycle of the stock is a long one, the rate of change will be small, and vice versa" (Wegener et al., 1986, p. 3). Finally, the last column represents the possibility and degree of the process being reversed.

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In a similar way, this has also been identified in SES theory under the concept of Panarchy and the adaptive cycle developed by Gunderson and Holling (2001). However, Gunderson and Holling (2001) add to this discussion by arguing that the slower processes of change tend to happen at the higher system/spatial scales. This has been discussed in further detail in later chapters.

Table 7: Urban change processes as presented by Wegener et al. (1986, p. 4)

Level	Change Process	Stock Affected	Response Time (years)	Response Duration (years)	Response Level	Reversibility
1 Slow	Industrial construction	Industrial buildings	3-5	50-100	Low	Very low
	Residential construction	Residential buildings	2-3	60-80	Low	Low
	Transport construction	Transport system	5-10	>100	Low	Nearly irreversible
2 Medium Speed	Economic change	Employment/ unemployment	2-5	10-20	Medium	Reversible
	Demographic change	Population/ households	0-70	0-70	Low/high	Partly reversible
	Technological change	Transport equipment	3-5	10-15	Medium	Very low
3 Fast	Labour mobility	Workplace occupancy	<1	5-10	High	Reversible
	Residential mobility	Housing occupancy	<1	5-10	High	Reversible
	Daily mobility	Traffic	<1	2-5	High	Reversible

To summarise: there is no one way to study cities as complex systems. It can be useful to use models to describe some aspect of the city, but we must keep in mind, for any model to truly represent the real world, it will have to be as complex as the real world (Cilliers, 1998, p. 58). The majority of models have a particular goal in mind, but they all seek to understand and explain the process of self-organisation. Batty (2007, pp. 21–24) has described that there are five main processes that drive change in the city, while Wegener et al. (1986) have explained that the various processes that drive change happen at different speeds and that the system will respond differently to different changes at different rates.

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2.8. Conclusion and the way forward

This chapter started off by describing how our approach to science in general and to studying the city has changed from the modernist, reductionist approach to understanding that the world and cities in which we live are in fact systems and are far more complex than we first thought.

It went on to define what a system is and why it is important that we study the world as a system, since traditional approaches viewed the city as static and near equilibrium. We now know this is not the case and they are, in fact, dynamic and far from equilibrium.

We now know that complex adaptive systems are made up of many agents and that these agents interact in a non-linear way with the result that these interactions mean that the system is more than the sum of its parts. The distinction was made between various classes of systems, of which complex adaptive systems are Wolfram class IV systems and lie on the edge of order and chaos. A further distinction was made that there are systems, complex systems and complex adaptive systems. The latter are the focus of this study.

From this point, the focus was on understanding what complex systems are and how they work. To do this the main properties of any CAS were identified and described, i.e. that systems are comprised of adaptive agents that aggregate together to form higher level aggregate agents. By interacting, these agents create a flow of information and resources between them. Because of the non-linear nature of the interactions and the flows of information, the agents begin to organise themselves without any top-down direction in a process called self-organisation. From this bottom-up process, global system behaviour *emerges* at a system level. This is also a result of the CAS being made up of systems that create natural hierarchies of interconnected sub-systems. Diversity and redundancy is another important aspect of the system. Diversity helps not only to create and exploit niches within the system, but also to create redundancies which in turn help to bring stability and resilience into the system. Finally, the system cannot be seen in isolation as all CAS are, in fact, open systems, i.e. the system is open to and interacts with its environment. Through the course of this interaction with its environment, the system is influenced by and influences its environment. Through these interactions, the system adapts and evolves to changes in its environment while the environment, in turn, adapts and evolves to changes in the system in a process called co-evolution.

After that, how a city can be seen as a CAS was described. How the properties of a CAS emerge in a city was explored and some examples given. When asking how we study cities as CAS and how we understand urban change, it was found that there are five main overarching, drivers of urban change according to Batty (2007): randomness; historical accident; physical determinism; natural advantage and comparative advantage. When reviewing how cities are studied as CAS, it was established that there is no one specific way to do this, but that many researchers use computer models to help understand the self-organisation process that found cities. As O'Sullivan (2004, p. 288) and Rotmans (2006, p. 160) have indicated, models are valuable for understanding the city but they have their shortcomings. It is partly for this reason that this study and the framework to follow was developed.

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The next chapter will elaborate on the methodology followed in this study. An overview of the research design and method used will be given, after which a brief introduction will be presented of two case studies used as examples to help illustrate how the framework can be used. This will be followed by a short description of the broader framework, which will then be explained in further detail in chapter's four to six.

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Chaper 3: Methodology & research design

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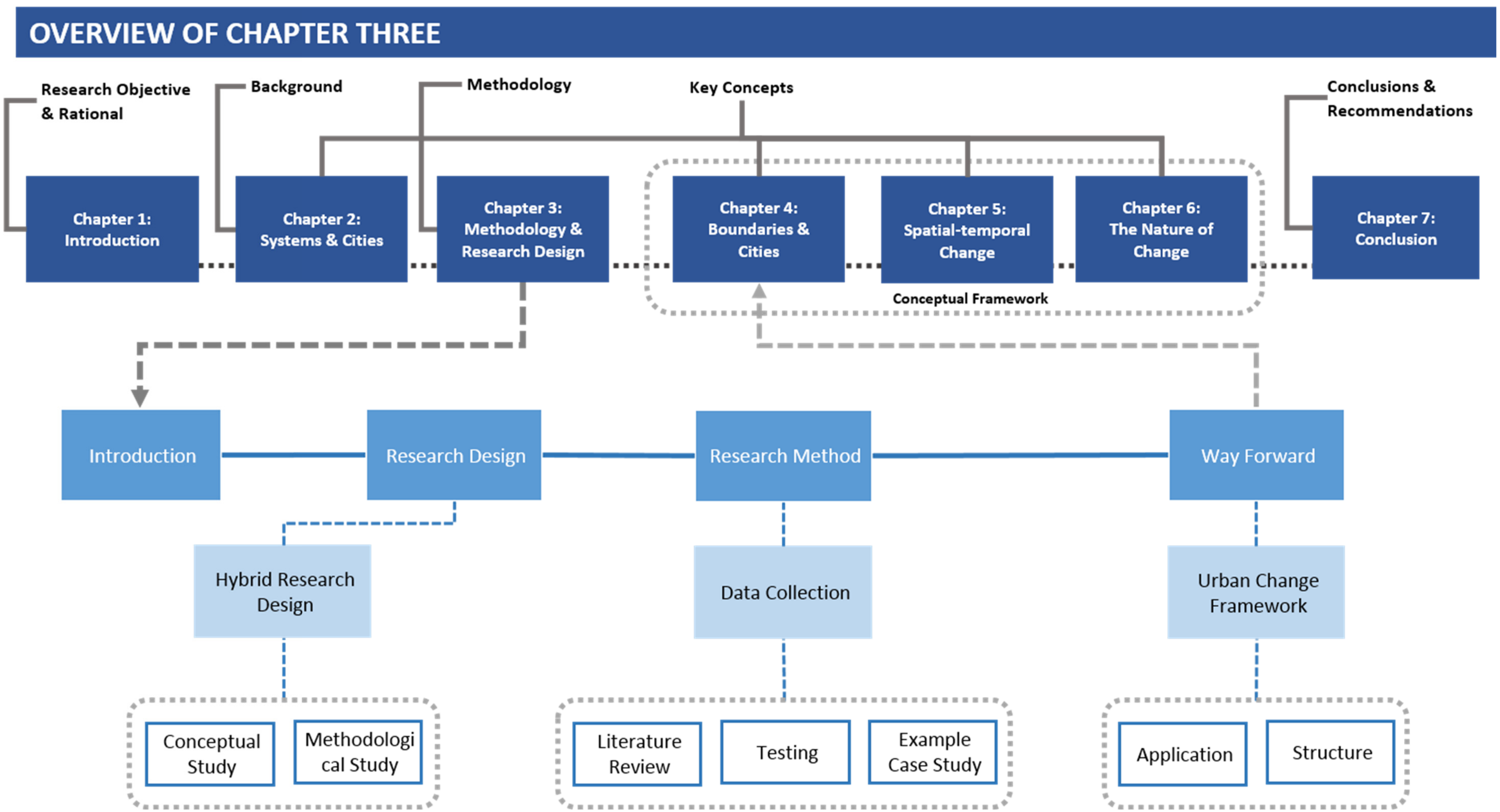

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3.1. Introduction

"Every discourse, even a poetic or oracular sentence, carries with it a system of rules for producing analogous things and thus an outline of methodology"

(Jacques Derrida in (Weber, 1995, p. 200)

As the quote above highlights, a methodology is essentially a set of rules, practices or processes which can be used to solve different problems (Mouton, 2001, p. 56). In responds to the problems and objective of the study identified in Chapter 1 this chapter will describe the method that was followed in order to respond to these challenges and objectives.

The previous chapter showed that cities are complex adaptive systems and that a complexity theory based approach can and has been used to describe the urban system and how it changes. The purpose of this chapter will be to present the research methodology used in this study, with a particular focus on responding to the last research objectives. The objectives being (1) the identification of a theoretical basis that can describe the behaviour and changes in cities. (2) The development of a framework that can describe the urban system. (3) The translation of SES theory constructs for mapping change into the urban context and (4) to illustrate how these concepts can be applied into the urban environment.

A qualitative approach has been used with in this study. However, this has been supplemented at points with quantitative information in order to further support the arguments within the dissertation. For this reason this study makes use of a mixed methodology or hybrid research design. The sections to follow will describe the research design. This will be followed by a description of the research method used.

Lastly, as one of the objectives of this study is to illustrate how the concepts presented within this dissertation can be applied into the urban environment two case studies will be used as a means to test, apply and illustrate the application of the concepts within the urban environment. The background of the case studies will be presented, as well as the case studies themselves. The chapter will conclude by providing a short overview of the process that will be followed in order to achieve the research objectives.

3.2. Research design

A research design can be roughly defined as the planned process or strategy that will be followed to achieve the desired result (Leedy and Ormrod, 2010, p. 3; Mouton, 2001, p. 57; Welman et al., 2005, p. 52). This study will make use of a hybrid methodology approach comprising two research designs. The first of these to be discussed is a non-empirical conceptual study. This type of research design focuses on engaging with and understanding concepts and theories so as to add to our body of knowledge about these theories or concepts.

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The second research design that will be used is an applied methodological study research design. Applied methodological study research designs are typically done in conjunction with other research designs and are normally used on explorative research. These designs normally focus on developing new methods of data collection or to validate existing tools (Mouton, 2001, p. 173).

3.2.1. Conceptual study (non-empirical)

Maree (2007, p. 71) describes the characteristics of a conceptual research design as being “largely based on secondary sources, that it critically engages with the understanding of concepts, and that it aims to add to our existing body of knowledge and understanding”.

Based on the first objective of this dissertation, identify a theoretical basis to describe the behaviour and changes of cities, as well as the description by Maree (2007, p. 71) on the characteristics of a conceptual study, it can be argued that a conceptual approach is the most appropriate research design for this study. This is especially true when we consider that “In conceptual studies the data with which we work is concepts” (Maree, 2007, p. 72). Thus the data used in this study can be seen as theoretical concepts with regards to cities and urban change. Furthermore, from the literature complexity theory was identified as the most appropriate theoretical basis for use in this study. From there the concepts and ideas from complexity theory as applied to the urban setting can also be seen as form of data.

This is further supported by the fact that conceptual studies often “tend to be abstract, philosophical and rich in their theoretical underpinning” (Maree, 2007, p. 72), which is an apt description for this study as it provides a theoretical basis before the application of the theory is presented. Conceptual studies are conducted through a “critical analysis of the literature [that] is intrinsic to the concept analysis, more so in the case of studies that deal with a concept that has displayed a variety of contending meanings in which the literature is almost infinite” (Maree, 2007, p. 72). The discussion of the literature in Chapter 2 illustrated that complexity theory can be used as a theoretical base to describe the behaviour and change of urban areas. Furthermore, in the case of the literature on complexity science (and its application), this may very well be the case, as it is a growing field of study.

Among the key characteristics of research questions typical of conceptual studies/research designs are that they attempt to clarify “conceptual linkages though classification and categorisation” (Mouton, 2001, p. 175). This characteristic is address in the third objective where SES and resilience theory constructs for mapping change are translated into the urban context.

The meta-theory used by a conceptual analysis study includes, for example, debates around the differences “between modernist and postmodernist assumptions and beliefs” (Mouton, 2001). This study, through the very nature of complexity science, challenges the position of the modernist, reductionist perspective; but its aim is not to interrogate modernism.

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3.2.2. Applied methodological study research design

Methodological studies are often explorative in nature and are typically aimed at developing new methods of data collection or to validate different tools (Mouton, 2001, p. 173). As this study seeks to, in part, explore and validate the application of concepts and tools derived from CAS and SES theories on the urban environment, an applied methodological study research design is also seen as appropriate for this study. Additionally this type of research design is often done in conjunction within other research designs (Mouton, 2001, p. 174), meaning that methodological studies can often be found within hybrid or mixed methodology approaches to research.

Methodological studies typically fall under the umbrella of meta-research designs. As such they tend to have various core logics and utilise multiple types and sources of data, this includes primary and secondary data as well as qualitative and quantitative data (du Toit, 2010, p. 5; du Toit and Mouton, 2012, p. 8; Mouton, 2001, p. 173). The majority of the data that this study makes use of is secondary data, which is primarily in the form of qualitative data which has been taken from the theories and concepts from the literature as well as in the utilisation of the case studies as a means to test the application of the identified tools on the urban environment. Qualitative data has been used at various points as a way to further support the application of the tools.

The application of the applied methodological study research design is used to respond to the second and fourth research objectives, i.e. (2) the development of a framework that can describe the urban system and (4) to illustrate how these concepts can be applied into the urban environment, as it aims to apply and validate the tools taken from CAS and SES theory onto the urban environment.

3.3. Research method

A conceptual research approach calls for an in-depth understanding of the concepts found within the literature. For this reason an extended literature review was conducted. From the literature the theoretical underpinning of the proposed framework where identified and explored. The initial concepts developed from the literature were submitted for critique at various international conferences[22] (see Landman and Nel (2013, 2012), Nel et al. (2013) and Nel and Nel (2012)). Additionally, numerous discussions and workshops with colleagues and peers were also used to further refine and test ideas.

As part of the process of developing the concepts and in application of the applied methodological study research design two case studies where used as a means to test the application of the concepts and ideas discussed within this study. These two areas were used for several reasons. The reasons being that both neighbourhoods were established within a few years from each other, they are within close proximity to each other, large amounts of longitudinal data was available for both areas (which is an important aspect for this study), both areas have a unique history and characteristics.

[22] See Annexure 1 for a list of conferences

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3.4. Irene and Lyttelton as examples

As mentioned above two case studies will be used to demonstrate how the concepts found within the study can be applied within the urban context. The following provides a brief background to the case study areas and their histories. This is done to provide the reader with some context to the study.

3.4.1. Study background

The data for the examples to be used was collected in 2011 as part of an honours dissertation[23] (Nel, 2011). The research was primarily aimed at identifying the drivers of spatial change within South African neighbourhoods and explored how two neighbourhoods changed spatially over a period of 100 years. Two case studies were undertaken of two neighbourhoods within the city of Tshwane: Lyttelton Manor (Lyttelton) and Irene. These neighbourhoods are in close proximity to each other but have developed very differently over the past one hundred years. Figure 25 provides for a locational map of the two neighbourhoods. The study involved an historical overview of the two neighbourhoods' development histories, and considered some of the social and economic factors that played a role in terms of spatial change. The findings of this research suggest that, in the case of Lyttelton and Irene, the availability of water, community attitude to development, location in relation to employment centres such as Centurion and Pretoria's central business districts, as well as the services and retail facilities that are in close proximity, are amongst the biggest forces that have shaped these neighbourhoods (Nel, 2011).

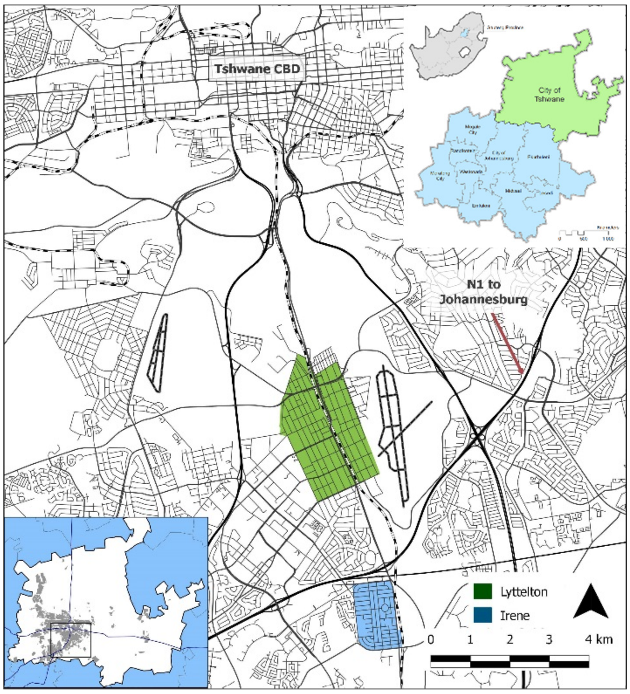

Figure 25: Right the location of the Irene (bottom) and Lyttelton Manor (middle) in proximity to Tshwane (Pretoria's) CBD (top). Source Nel and Landman (Forthcoming)

However, it was not any one specific factor at any one point in time that caused the most change in these neighbourhoods. It was, rather, a combination of forces working on and around them in different ways that made the difference in how they developed and changed over time. The data collected in the mentioned study will be reinterpreted for use in this study in an attempt to illustrate how the proposed framework can be applied

[23] Some additional data has been collected since the completion of the study and will be also be used to further support the argument.

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3.4.2. Short overview of the history of Irene & Lyttelton

Irene's history dates back to the Second Anglo Boer War when the land was used as a concentration camp by the British. After the war, in 1902, the village of Irene was established along the old Pretoria-Johannesburg railway on a portion of the farm Nellmapius. It was established by A.J van der Byl as an outlet for his dairy farm. Over the next 40 years, the village grew steadily. In 1940, the village came under the jurisdiction of the Pretoria Peri-urban Areas Health Board and was later incorporated into the growing municipality of Lyttelton. This also marked the creation of the Irene Village Association, which played a major role in shaping the future of Irene. During the 1950's, the Irene Oval, a recreational park, as well as Irene extension one (Irene X1), was established as a retail outlet for Irene. In the 1960's, the Irene Village Association played a key role in the rerouting of many roads to be built or upgraded next to the village. This pattern of closing off and protecting the community from change continues to this day, as the community is now a closed off security community with limited and controlled access into the village proper (Nel, 2011).

Lyttelton Manor (Lyttelton) was also established along the Pretoria – Johannesburg railway at much the same time (1908) as Irene and just a few kilometres away. The neighbourhoods are about 5 km apart (station to station). However, unlike Irene, Lyttelton did not experience much development in the early stages. This was due to the limited water supply at the time. When Lyttelton did obtain a permanent supply of piped water, it started to develop rapidly due to its close proximity to the two air force bases, Waterkloof and Swartkop, as well as ISCOR (South African Iron and Steel Industrial Corporation) and ARMSCOR (Armaments Corporation of South Africa) which allowed it to maintain its rate of development. Lyttelton Municipality was expanding at a rapid rate and, in 1967, its name was changed to Verwoerdburg. The original township retained its name but became a suburb of the town of Verwoerdburg. During the 1980's, Lyttelton underwent some major changes with the building of a retirement village and a flood of subdivision applications. This prompted the municipality to implement a subdivision and urban development policy to manage and guide where this new development could take place. This urban renewal policy also encouraged changes in land-use to non-residential along the major roads. This caused the neighbourhood to become somewhat fragmented even though, due to the presence of schools, it still maintains a primarily residential function (Nel, 2011).

3.5. Moving forward

In order to conduct this study, a mixed method was used which was comprised of a conceptual study and an applied methodological study research design. This was done as a conceptual study is best suited to dealing with theoretical concepts as a source of data while an applied methodological study research design allows for the application and testing of tools.

In following the research design set out above, a desktop study was conducted as the primary means of collecting data. From this a theory, in this case a framework, was developed of which parts were

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then tested at various conferences for validity and feedback on the work done. To further help test and illustrate the application of the framework in the urban context, two case studies of neighbourhoods were used.

Figure 26 shows the outline and main structuring elements of the proposed framework for studying urban change. The proposed framework is comprised of three main components. Each section of the framework to be discussed be given a rational and theoretical discussion, after which examples taken from the case study will be given to illustrate and test the application of that particular section of the framework.

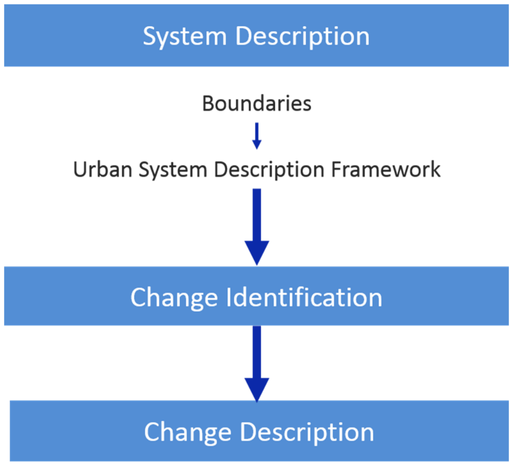

Figure 26: Outline of the proposed Framework for Urban Change

The role of the framework is to provide a process whereby the user has an alternative means to describe the particular system or sub-system (area) of interest and then to be able to begin to describe/make sense of the complexities without getting lost in them. This framework has its roots within complexity theory as it provides a theoretical means to tackle the complexities inherent within complex systems, as cities can be seen to be.

Chapter Four explores the first part of the framework, that being how to describe the urban system. To achieve the goal of describing the urban system, the framework has been broken down into two sub-components, i.e. setting boundaries and a sub-framework for describing the urban system, the Urban System Description Framework.

The second section of the framework for describing urban change, explored in Chapter Five, looks at understanding identifying change within a system. This will be approached in two ways. The first being time as an important factor to be included in the framework as the goal is to study change within the city. The second type of change to be considered is that of change across spatial scales. Once the changes have been identified making sense of the changes becomes the next important factor.

Chapter six looks at the final section of the framework, describing change. This chapter brings the pervious sections together and begins to make sense of the identified changes. Throughout the following chapters reference will be made to the case studies as they will be used to illustrate and test the application of the tools described within the dissertation.

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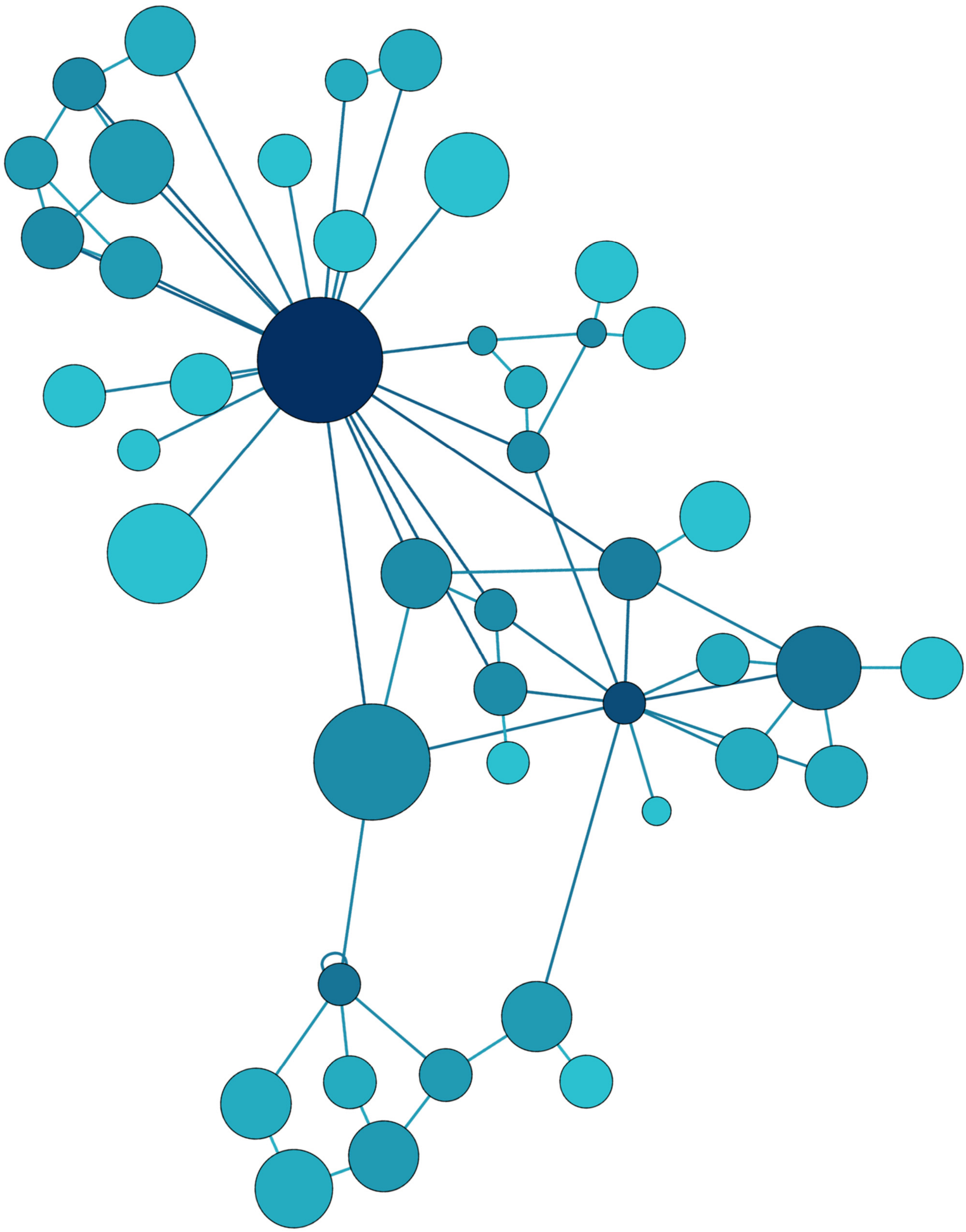
Chaper 4: Boundaries & describing cities



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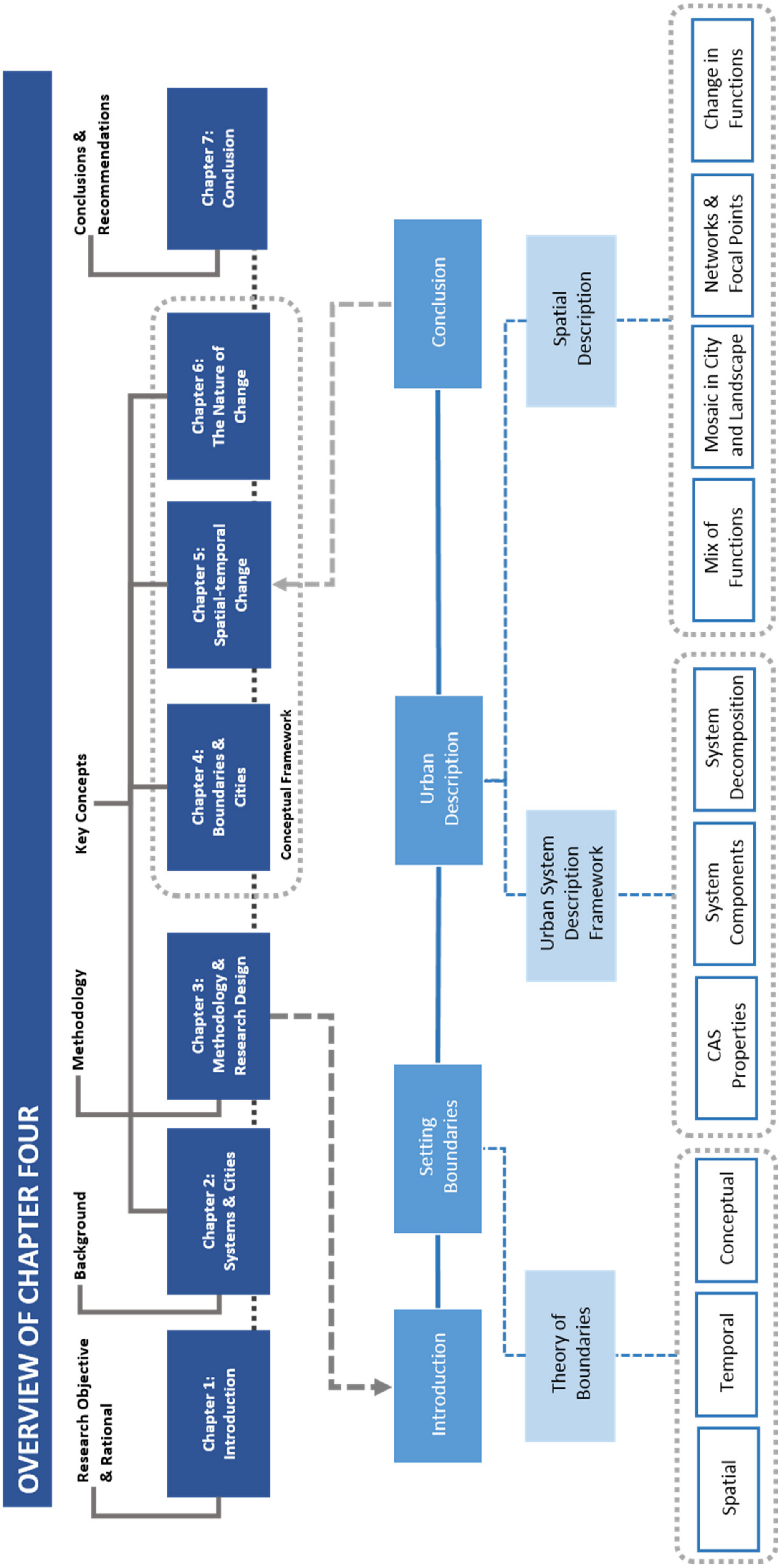

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4.1. Introduction

"Strong reductionism, where the aim is to reduce the complexity faced to a neat, comprehensive model or algorithm, becomes impossible. We cannot know complex systems completely" … "This implies that the possibilities which a model holds will always be the product of the frames we apply because we cannot comprehensively determine the limits of the system and hence accurately define the field of possibilities"

(Human and Cilliers, 2013, p. 2)

In the previous chapters, the theoretical background to this study was discussed. It was argued that traditional approaches to studying the city are insufficient as they see the city as being static and close to equilibrium. It was then argued that cities are in fact complex adaptive systems which are dynamic and are far from equilibrium and, to study change in cities, a complex adaptive systems approach is the most appropriate method. The framework to follow is based on this theoretical grounding. The following chapters will develop and describe the framework for identifying and describing urban change.

Walker et al (2002) presents a framework for analysing social-ecological systems resilience. The first step of this framework is to define the system, following which changes that have occurred over time should be identified. The first step of this framework echoes the overarching goals of this study, to describe the urban system and how it changes. To achieve this step, Walker (2002, p. 8) asks a series of questions, of which the ones relevant to this study have been presented below:

- "What are the spatial boundaries of the SES?"
- "What are the key components of the SES?
- "What is the historical profile of the system? How did it get to be what it is now—what changes occurred through its history in terms of ecosystem, technology, society, economy"

As this study and the first part of Walker el al.'s (2002) framework have similar goals, these questions seem to be useful guiding points for this study, but the questions have been adapted to better suit the nature of this study to:

- What are the boundaries of the urban system?
- What are the key components of the urban system?
- What changes occurred throughout the systems history?

This chapter considers how the first two questions can be answered, i.e. what the boundaries and components of the system are. This will be done by reviewing the theory and process of system boundaries and how to define them. This will be followed by an exploration into the components that make up the urban system. The final question will be explored in more detail in chapters five and six.

The following chapter will describe the first part of the proposed framework for urban change, which consists of the *Urban System Description* section. The chapter will be divided into three parts. The first will focus on the challenges of setting boundaries around a particular study area. The second will

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describe a sub-framework within the larger framework (called the Urban System Description Framework (USDF)), whose purpose is to provide a means to describe an urban system over a given time period. The third part of this section will then look at how the various properties of complex adaptive systems can be translated into the spatial dimension.

Throughout this section, examples from Irene and Lyttleton will be used as a means of illustrating how the concepts can be applied. At the end of this section, how the urban description component of the framework integrates into the larger framework will be considered, after which a summary and conclusion for this section will then be provided before going on to the next chapter.

4.2. Setting boundaries

"There is no clearly determinable boundary between the sea and the land, between sociology and anthropology, between an automobile's exhaust and your nose. There are only boundaries of word, thought, perception, and social agreement—artificial, mental-model boundaries"

(Meadows, 2008, p. 95)

4.2.1. Introduction and rationale

As a part of this study seeks to explore and describe complex systems, we need to know how to identify what is being studied. Setting boundaries helps us to identify what visible and virtual (intangible) interactions we take into account (Holland, 2012, p. 3). The above quotation by Meadows (2008) highlights one of the issues that become apparent when studying complex systems, namely the difficulty of setting clear system boundaries. Setting boundaries in a study is a vital part of any research as it allows the study to have focus and to be manageable (Hofstee, 2010; Leedy and Ormrod, 2010; Neuman, 2011; Welman et al., 2005). However, this task becomes exponentially more difficult when dealing with complex systems. This is "because systems rarely have real boundaries. Everything, as they say, is connected to everything else, and not neatly" (Meadows, 2008, p. 95). This is made even more difficult as complex systems are open to their environment, which results in difficulties in identifying and setting clear boundaries (Cilliers, 2005a, p. 5). There is no clear consensus within the literature on how to set boundaries; only that they should be set (Chu et al., 2003, p. 19).

This section will describe the importance of setting boundaries when studying complex systems, identify different types of boundaries, and provide some examples of how this can be done. An explanation will then be given of how this fits into the next section, as well as the larger framework.

4.2.2. Theory of boundaries

If setting boundaries is a difficult task, can we work without them? Cilliers (2005a, p. 612) argues that "Boundaries are still required if we want to talk about complex systems in a meaningful way—they are in fact *necessary*". Setting boundaries allows for identification of the system or its sub-systems, as well as its components. As a result, a system must be bound in some way if we are to study it effectively. However, this becomes difficult because, as soon as one tries to set boundaries to a

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system, one meets challenges, among the foremost of which is the fact that systems are open to and interact with their environment and are often nested within larger systems (systems within systems), making it extremely difficult to study as there is no clear line of where the focal system (the system or part thereof that is being studied) starts and ends (Chu et al., 2003; Cilliers, 2005a; Cudworth and Hobden, 2012; Human and Cilliers, 2013; Meadows, 2008; Ostrom, 2007; Resilience Alliance, 2010). In addition, when we apply boundaries, we find that the "greatest complexities arise exactly at boundaries" (Meadows, 2008, p. 95) which further compounds the difficulties.

So then, how do we set boundaries on a system? Cilliers (2005a, p. 610) suggests one way of managing the difficulties of boundaries is to use the concept of 'operational closure'. Operational closure suggests that some systems can create their own boundaries through a process if 'internal reproduction'. This internal reproduction process allows a system to maintain its identity. This is similar to Holland's (2012, pp. 15–19) description of how niches within a system help to form boundaries. Additionally, Meadows (2008, p. 83) maintains that natural boundaries tend to appear along sub-system boundaries. This is because the connections within sub-systems are stronger than those between sub-systems. Meadows (2008, p. 83) further discusses that hierarchies within systems help to create sub-system boundaries and, when hierarches collapse, they tend to tear along sub-system boundaries. Norberg and Cumming (2008, p. 246) indicate that "Determining the system boundary typically involves assessing system properties across a range of scales to determine which scales are of greatest interest".

Human and Cilliers (2013, pp. 2–9) argue that setting boundaries to define a system will always depend on the context and be driven by what we prioritise. As a result, we will always exclude some facets of the system being studied. This argument is further supported by Chu et al. (2003, p. 23), Cilliers (2005a, p. 610) and Meadows (2008, pp. 95–99). Meadows (2008, p. 99) argues that "boundaries are of our own making, and that they can and should be reconsidered for each new discussion, problem, or purpose", while the Resilience Alliance (2010, p. 10) adds to this by saying that the boundaries that are used should be 'issue' (or question) driven; i.e. how we draw boundaries depends on the question(s) being asked.

From this, we can conclude that setting boundaries on the system we are observing is important and, when setting boundaries, we should not and cannot include the entire system. The way we set our boundaries should be done based on what is being investigated, as well as how this is being done. Cilliers (2005a, p. 610) cautions not to "overemphasise the closure of the boundary". What this entails is that we should not see the boundary as a fixed entity, but that it should be semi-open so as to recognise external interactions outside of our boundaries. Additionally, we can argue that, as new information presents itself, it may become necessary to re-evaluate the boundaries that have been placed.

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What types of boundaries do we use? For the purpose of this framework and the examples used, three different types of boundaries can be considered, see Figure 27. These are *spatial*, a boundary that can be drawn on a map (Cilliers, 2005a, p. 610; Resilience Alliance, 2010, p. 10), *temporal,* a boundary across a specified time period, (Norberg and Cumming, 2008, p. 246; Resilience Alliance, 2010, p. 10), *intangibles*, the number of non-physical human and or non-human aspects that will be included; i.e. social, economic, institutional, as well as the/a study limitations (Cilliers, 2005a, p. 612, 2001, p. 6; Norberg and Cumming, 2008, p. 247).

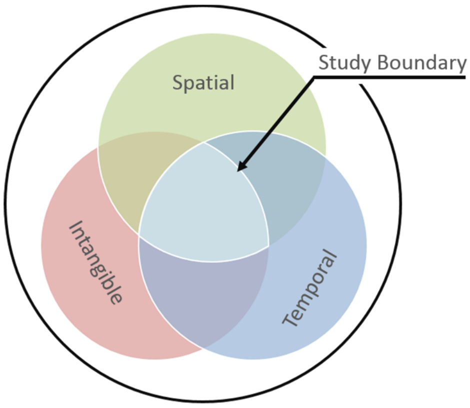

Figure 27: Three different types of boundaries

4.2.3. Irene and Lyttelton's boundaries

Temporal boundaries are necessary as CAS are dynamic, implying change over time, with the result that we cannot look at them as static entities. To understand them, we must look at their behaviour over a particular time period (Norberg and Cumming, 2008, p. 246). Holland (1992a, p. 20) argues that

> "the primary reason for adopting a discrete time-scale is the simpler form it confers on most of the important results. Also this formalism intersects smoothly with extant mathematical theories in in several fields of interest where much of the development is based on a discrete time-scale".

Holland (1992b, p. 20), Norberg and Cumming (2008, p. 247) and Holling et al. (2001c, pp. 64–68) suggest, if the overall goal is to study change over a long period of time, 110 years for example, one needs to set two types of temporal boundaries. The first being the study time boundary and the second being sub-focal temporal boundaries. The study time boundary can be seen as the overall time period that is to be investigated by the study, while sub-focal temporal boundaries are the time intervals into which we can break the study time boundary. This is done to make the study manageable.

In the case of our examples of Irene and Lyttelton, the study time boundary was 1900 – 2010 (110 years). To manage the amount of information gathered and to be able to put it into the UDF, to be explained below, the 110 year time period was broken into ten year time periods (sub-focal temporal). The reason a ten year period was chosen was because it was a long enough period for there to be change, as well as the data allowing for this interval.

The **spatial boundaries** were selected at the neighbourhood scale as "the neighbourhood scale is perhaps the best scale to consider in an assessment of the sub-system. From this scale one can look up and down onto the larger and smaller scales of the city as a whole, as well as individual buildings and what effect they have on this sub-system"(Landman and Nel, 2012, p. 3). The neighbourhoods and thus the spatial boundaries, for the two areas were derived from the original township

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boundaries, which coincide closely with Census data (1996, 2001 and 2011[24]), as well as older sources of information. The spatial boundaries for Irene and Lyttelton can be seen in Figure 28.

Figure 28: Spatial Boundaries placed on Irene (*left)* and Lyttelton (*right)*. The roads have been highlighted in white

The availability of data, as well as the specific focus of the study, on the drivers of spatial change, created the **intangible boundaries** of the study. As a result, for Irene and Lyttelton, the intangible boundaries were limited to social, economic and institutional factors that influenced spatial factors within the two neighbourhoods.

New insights in one area, i.e. intangibles, may necessitate a change of the boundaries in another, i.e. temporal (see Figure 29). As a result, the boundaries placed should not be static. Rather, they should be in a constant state of change.

[24] 2011 Census was not included in the original study, as the results had not been released yet, but where possible it has been added as an additional source of information to further show the changes in the two areas.

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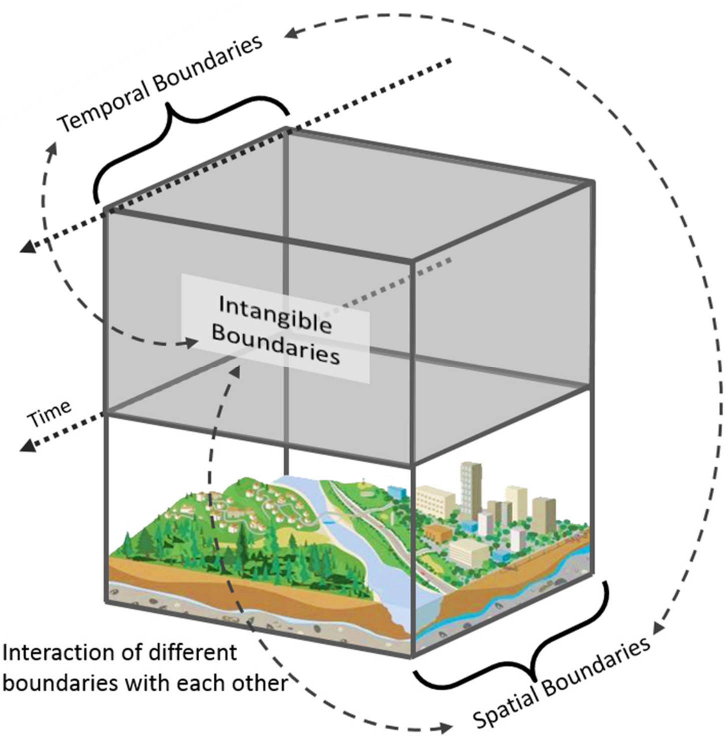

Figure 29: Interactions of the different boundaries resulting in state of constant revision of the placed boundaries for a particular study. Part of image adapted from ESRI.com

4.2.4. How do boundaries fit within the larger framework?

As discussed in this section, boundaries are essential when studying complex systems and no study can proceed without them. However, this becomes increasingly difficult due to the open nature of complex systems. Because systems tend to be better connected internally within the sub-system than between sub-systems, natural boundaries tend to form along these lines (Meadows, 2008, p. 83). This may be one way of identifying natural boundaries within complex systems.

If natural boundaries cannot be found, then the boundaries should emerge out of the investigation or research question, as described by Cilliers (2005a, p. 610). The easiest way to manage the issue of

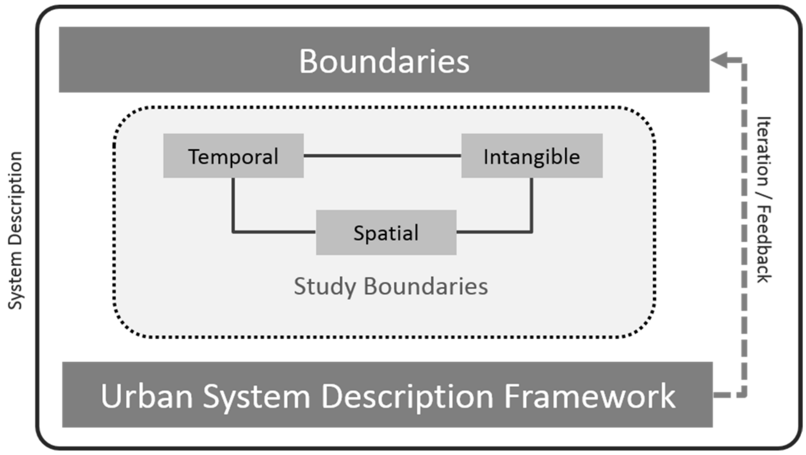

Figure 30: Boundaries link with the urban description framework

setting boundaries on a system may be by asking specific questions about the system (Resilience Alliance, 2010, p. 10) or by using a system driven approach, whereby the system's boundaries can be identified through investigation of how the system's properties present themselves (Norberg and Cumming, 2008, p. 246). Boundaries frame the investigation and form the initial part of the framework. The initial boundaries may have to be changed as the study progresses due to the fact that the boundaries of the study are often determined by the assessment of the system properties (Human and Cilliers, 2013, p. 2; Norberg and Cumming, 2008, p. 246). What this means is that, as the description of the system under investigation is conducted, there should be re-evaluation (feedback) of the boundaries, as shown in Figure 30.

4.3. Urban Systems Description Framework

"If we cannot provide a system definition then we run the risk of continually trying to track a moving target"

(Norberg and Cumming, 2008, p. 246)

4.3.1. Introduction and rationale for the USDF

The previous section identified the need for boundaries and discussed the various types of boundaries in order to answer the first question derived from Walker et al. (2002, p. 8), that being: what are the boundaries of the urban system? This section's goal is to provide a means to help describe the urban system through the lens of complexity theory. This will be done by exploring a sub-framework of the larger framework which will be called the *Urban Systems Description Framework*, USDF for short.

The Urban System Description Framework is made up of three main concepts, as described in Figure 31. These concepts are: characteristics/properties of CAS, components of the urban system and the level of decomposability of the study. As previously discussed, CAS are normally described through their properties and, as cities are also CAS, as discussed above, this statement should hold true. The components of the urban system can be seen as sub-systems or different fields of study. This has been based on the above discussion on boundaries. If, for example, a study only focuses on social aspects, then the components of the urban system will be focused around that. But if the study is looking at the broader system as a whole, then there will a larger variety in terms of the

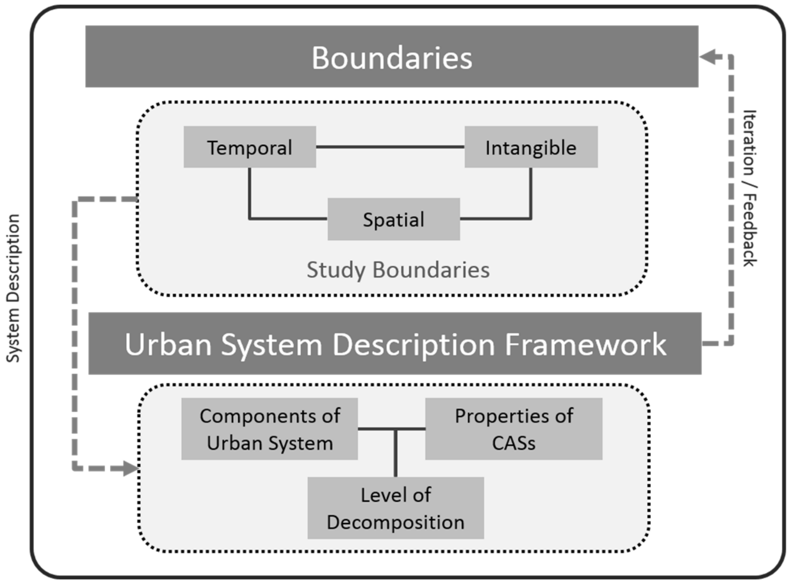

Figure 31: Urban Description component. Made up of setting boundaries and the urban systems description framework

components of the system. The level of decomposition looks at how far a particular component of the system can be broken down. This concept is based on the fact that systems are comprised of sub-systems.

This section of the framework will focus primarily on the softer aspects/components of the city (i.e. social, economic, institutional, etc.). However, it will include some of the physical/hard elements as well. They will be discussed in more detail in the next section. Some examples of the application of the framework will be given from the case studies of Lyttelton and Irene.

4.3.2. How should cities as systems be described?

As the previous chapters have explained, cities are complex adaptive systems and there are many different methods to study them, many of which include computational modelling among others. But as Rotmans (2006, p. 160) highlighted, many of these models cannot take qualitative aspects into account. If computational models are not the answer, then what is? This section seeks to provide a solution by presenting a framework that takes qualitative and quantitative elements and bringing them together.

The first step in creating a framework for the description of the urban environment is to identify what elements this type of framework should consist of and what it should be able to do. Du Plessis (2008a) provides a list of the minimum aspects that should be considered when studying social-ecological systems which, as discussed, are also complex adaptive systems. The aspects that du Plessis (2008a, pp. 67–68) lists for identification are: "the main system entities and how they are linked, cross-scale structures and linkages in the system, and the aspects that determine its behaviour and dynamics".

Du Plessis (2008a, p. 68) reasons that there are many qualitative and quantitative methodologies available to study SES. However, they are more often a mixture of methodologies selected "according the requirements of the different phases of research and the related needs to extract, process and synthesise data" (Du Plessis, 2008, p 67). As a result, the framework will have to be compatible with a multitude of different methodologies.

Ostrom (2007) describes a nested framework that discusses how to look at the interaction of linked SES, which is one of the aspects that du Plessis (2008a, p. 67) highlights as important when looking at SES. Below is a discussion and outline of the framework developed by Ostrom (2007).

Ostrom's (2007) framework for considering the interactions and outcomes of SES does not include details, as it focuses on managing commons. Rather, the argument for it and the overarching approach of the framework is on the ability of a system to be partially decomposed and thus 'broken' into smaller, more manageable bits.

Decomposability of a system can simply be described as how components at a lower level of a system are parts of higher level components (Ostrom, 2007, p. 15182). This concept is similar to Gunderson and Holling's (2001) concept of a Panarchy, in which higher level systems are comprised of lower level 'nested' systems, as well as Holland's (2012, 1996) notion of aggregation and hierarchy as a property

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of a CAS. Mitchell (2009, pp. 109–110) suggests that partial decomposability happens within hierarchical systems because the connections within sub-systems tend to be stronger than the connections between sub-systems. This creates natural boundaries between sub-systems. Holland (2012, pp. 15–17) refers to the fact that the level of hierarchy to be studied depends on the question being asked and can decomposed even further at whichever level is being studied if needed.

Ostrom (2007, p. 15182) describes three important aspects of decomposability of sub-systems that are needed to further understand the complexities of SES. These aspects are:

1. Conceptual partitioning of variables
2. The existence of relatively separable sub-systems
3. Complex systems are greater than the sum of their parts

The first aspect, the "conceptual partitioning of variables", is the division of variables and components into classes and subclasses. This is done to build a clear and collective scientific understanding of the system that is being studied (Ostrom, 2007, p. 15182). For use in this study, this can be seen as dividing the system into sub-systems or looking at the various components of the city (i.e. economic sectors). The ability of a system to be divided in to sub-systems/classes allows us to simplify complex problems into manageable 'chunks'. We do this by placing similar things into categories and then view them as being the same (Holland, 1996, p. 10). An example of this may be to look at different parts of the urban system in terms of the social, economic, spatial/physical aspects in order to better manage the complexities.

The second aspect is that some sub-systems are relatively independent of each other in some of the functions that they perform, although they do ultimately affect each other (Ostrom, 2007, p. 15182). Examples of this might be a road system and an economic system. For the most part, they function independently of each other but, if one, say the road system, were to stop functioning properly as the result of an accident on a major road, it would ultimately affect the economic system, as no one would be able to get to work and the economic system would suffer because of the lack of productivity.

The third aspect that Ostrom (2007) talks about is that complex systems are greater than the sum of their individual parts. This has been discussed in more detail in the previous section (see Chapter 2). However, what is worth re-emphasising is that it is important to "recognize that combining variables, for instance A, B, and C, can lead to a system with emergent properties that differ substantially from combining two of the original variables with a different one, say A, B, and D" (Ostrom, 2007, p. 15182), meaning that different combinations of variables will produce different results. What this means for this study is, if we consider the interactions of three particular variables and then observe the behaviour, we will get a particular result. However, if we add or replace a variable with another, we may see an entirely different set of behaviour. This is due to the emergent behaviour caused by the non-linear interactions between the agents. From what Human and Cilliers (2013, pp. 2–9) tell us, this may also hold true when observers from different backgrounds all study the same system but produce

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different results. i.e. an economist will view a particular system and see different behaviour to that of a sociologist viewing the same system.

Ostrom (2007, p. 15182) proposes a 'Nested Conceptual Map' as a general framework to use as a starting point to study linked SES. The framework has been adapted for this study and is illustrated in Figure 32. Each of the broad variables (different colours in the spectrum, Level 1), shown in Figure 32, can be broken into multiple sub-groups or categories. The level of abstraction in the sub-groups depends on the specific question being asked (Ostrom, 2007, p. 15182). The framework also "enables one to organize how these attributes may affect and be affected by the larger socioeconomic, political, and ecological settings in which they are embedded, as well as smaller ones" (Ostrom, 2007, p. 15182).

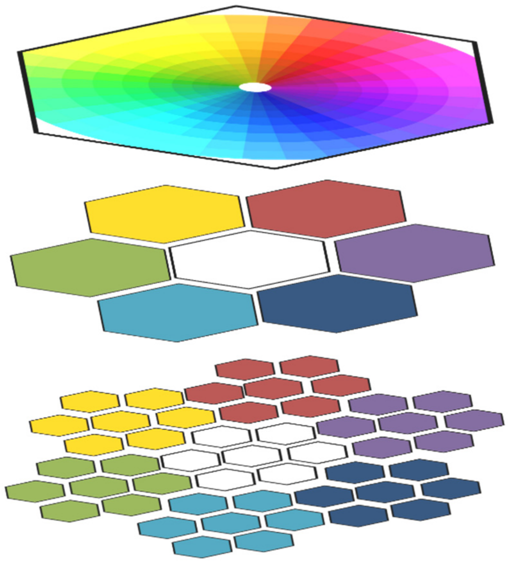

Figure 32: Ostrom's (2007, p 15182) proposed framework, 'The Nested Conceptual Map' for describing linked SESs [Adapted by Author].

From the above discussion, any frameworks to study complex systems and, by extension, social ecological systems, should have the following characteristics:

- Be able to identify -
  - The main system entities (agents) and how they are linked (interactions and signals) (du Plessis, 2008a; Holland, 2012)
  - Cross-scale structures and linkages in the system (du Plessis, 2008a; Holland, 2012; Ostrom, 2007)
  - Aspects that determine the system's behaviour and dynamics (this emphasizes the importance of looking at system behaviour over time) (du Plessis, 2008a)
- Allow for a mixture of research methods and tools (du Plessis, 2008a)
- Allow for and identify system decomposability (Ostrom, 2007)

And by using Ostrom's (2007) framework as a broad theoretical approach to describe complex systems, a framework for the purpose of describing the urban system can begin to take shape. This framework will be cantered around the fact, as the above discussion highlighted, that systems are nested into a series of sub-systems that can be partially decomposed into segments or compartments. If this is the case for all systems, then how would this look when considering the urban system? The next section begins to explore this question by examining how the urban system can be broken up into small sections to make it easier to study.

4.3.3. How to 'break (up)' the urban system

The section above highlighted that any framework to study CAS and SES must meet the set of characteristics laid out in the above discussion to achieve certain goals. The discussion also examined

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the framework presented by Ostrom (2007), which noted that systems are partially decomposable and can be broken into smaller sections, provided one takes into account that the sections still form part of a larger whole. However, if we are to achieve the objective of this study, to describe change in the urban system, we must first define the system and "In order to attempt to define the urban system, we must try to identify the components or entities of the system or of the sub-systems which form part of the urban system" (Reif, 1973, p. 26).

This section will begin to look at the urban system and, by using the concept of partial decomposability, how it can be simplified into manageable *bits*. This is done in order to answer the second question posed at the beginning of the chapter: What are the components of the urban system? As part of the process of identifying different components of the urban system, the different variables that can be used to describe the system will also be explored.

In her paper, Ostrom (2007, p. 15181) maintains that many "variables affect the patterns of interactions and outcomes observed in empirical studies", which is part of the reason why studying complex systems in a traditional way may no longer be a viable option. She indicates that, in previous studies related to sustainable resource governance, 30 variables were identified that played a role in affecting incentives, actions and outcomes of a system (Ostrom, 2007, pp. 15181–15182).

From this, she asks "how research can be conducted in a cumulative and rigorous fashion if this many variables [are] need to be identified in every study?" (Ostrom, 2007, p. 15182). Her answer is, although researchers need to be able to identify and measure many variables, not all variables are relevant to every study. This is because, she argues, SES are partially decomposable systems and there are different levels of connectedness between sub-systems (Ostrom, 2007, p. 15182).

With so many possible variables to consider, how do we decide what variables to use? Part of the answer comes from the previous discussion on boundaries, in which it was stated that boundaries can be set by asking a particular set of questions related to the system, thereby limiting the study and making it manageable.

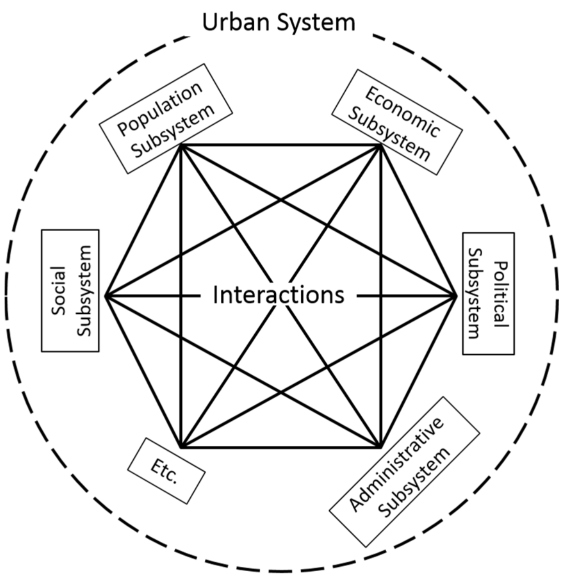

Figure 33: Urban system according to Reif (1973, p. 28)

Additionally, Reif (1973, p. 28) states that the "urban system can be considered to be structured by several parts or subsystems". From this, Reif (1973, p. 27) provides some examples of how the urban system might be broken into sub-systems, each of which have their own set of variables (see Figure 33 for an example of how Reif decomposes the urban system into various elements). Reif (1973, p. 28) also states that, although the urban system can be broken into several sub-systems, each of the entities contained within each of the sub-systems interacts within and across sub-systems (as illustrated by the lines joining the different sub systems in Figure 33).

4.3.4. The Urban System Description Framework (USDF)

Building on the discussion above, the proposed framework for describing the urban system will be presented in the text to follow. The USDF has been broken down into four parts, as shown in Figure 34: Level of decomposition, properties of CAS, components of the urban system, and the spatial description of the urban system.

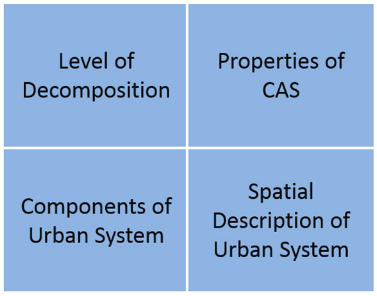

Figure 34: Four components of the

Underlying assumptions made to create the framework are that (1) The city is a complex adaptive system, which has been discussed in chapter 2, and will thus exhibit the characteristics and properties of a complex adaptive system. (2) Since a city is a CAS, it can be partially decomposed (conceptually) into various sub-components or sub-systems, as described in the discussion above. (3) Because the system can be partially decomposed, the sub-components can be studied in partial isolation. (4) Because we are studying urban systems, some of the characteristics can be seen spatially (Roggema, 2012; Salat, 2011; Salat and Bourdic, 2012b), as such, spatial descriptions will be included. It is also important to note that, because of the nature of CAS, made up of systems of systems (Gunderson and Holling, 2001), the cross-scale interactions must also be taken into account. This will be discussed in the next chapter. Building on the discussions in the previous sections, the proposed urban description framework is presented below.

4.3.4.1. USDF: Properties of complex adaptive systems

This section will discuss the first part of the USDF (Figure 35), the properties of CAS.

Complex systems can be described through their properties. As cities can also be seen as CAS, we should be able to describe CAS properties within the city. From the discussions presented in Chapter Two, this is indeed the case. As the properties of CAS and how they can be seen in the city has been previously discussed, this section will not go into detail on this topic. What will be presented is a list of questions that will enable the user of the framework to identify the CAS properties. The questions are presented in Table 8.

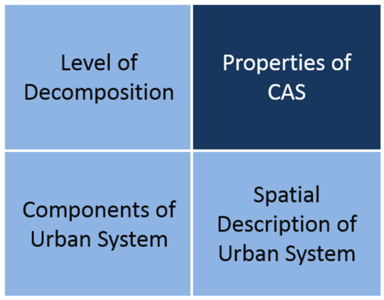

Figure 35: Properties of CAS as a component of the USDF.

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Table 8: Proposed questions to help identify the properties of CAS

CAS Property	Question
Agents	Who or what has agency (i.e. people, households, firms)? Who or what makes the system work? Who are the stakeholders? Are there any aggregate agents (i.e. firms, households)? What activities do the agents perform?
Adaption	What has changed?
Flows	Do the agents move? If so how? How are the agents connected? What type of connections exist? What moves between agents (i.e. information, money, goods)? How are the networks structured?
Self-organisation & Emergence	What are the trends or patterns observed at a system level that is a result of collective actions taken by individuals (i.e. population growth, traffic)?
Hierarchies	How does the system being studied fit into the bigger picture? Can the system being studied be broken into clearly defined sub-components/elements (i.e. social, economic, institutional elements)
Diversity	Is there any diversity in activity (i.e. land use)? Are there differences in the agents that make up the system (i.e. differences in race, culture, religion)? What, if any, are the differences in types of agents? Are there any differences in the composition of the agents or aggregate agents? Is there a diversity of routes through which the flows move (i.e. diversity transportation systems)?
Redundancy	Will the system continue to function if a part of it collapse (i.e. power blackouts or accidents on key though routs)? Are their back-ups for different parts or functions of the system? Can a function of the system be performed by another part or agent(s)?

4.3.4.2. USDF: Components of the urban system

This section will discuss the second part of the USDF (Figure 36), the components of the urban system.

As with any CAS, the urban system is comprised of several sub-systems (Reif, 1973, p. 27). These sub-systems can be further broken into sub-sub-systems which can, in turn, be broken down into further sub-components, and so on. Each of these can be seen as a CAS (Alberti and Marzluff, 2004, p. 247). The limit to how far the system can or should be broken down is set by the boundaries decided upon as well as the level to which the system or sub-system under consideration is being decomposed, as discussed in greater detail below.

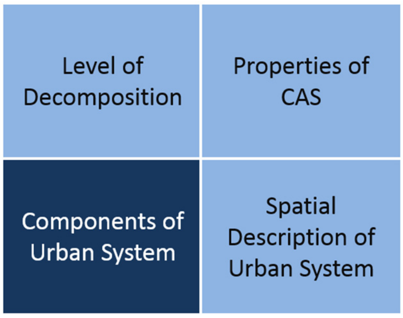

Figure 36: Component of the urban system as a component of the USDF.

The components that comprise the urban system will be somewhat different and dependent upon the particular study. The components under consideration will be determined largely by the question(s) being asked, the system (or city) being studied, as well as the boundaries placed on the system and the study. Because of the context specific nature of any study and system, it is an almost impossible task to give a complete list of all the components that make up the urban system. That being said, Reif

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(1973, p. 28) gives some guidance to help make this easier by suggesting the components that make up the city's sub-systems (see Figure 33 for an example of some of the possible sub-systems) be explored. Table 9 provides a non-exhaustive list of possible components that comprise the urban system. This list has been broken into four sub-systems.

Table 9: A non-exhaustive list of components of the urban system

Sub-system	Components	
Social	Schools University Banks Population (demographics) Social groups Sport	Religious institutions Friends Social media Hospitals Telecommunications Restaurants
Economic	Banks Industrial complexes Mining Shops (retail) Hospitals	Services industry Firms Farming Building Transportation
Institutional	Government departments Universities Banks	Public Transportation Law & the legal system
Physical	People Cars Animals Natural system (i.e. ecosystems) Roads	Weather Shops Factories Land

4.3.4.3. USDF: Level of decomposition

Decomposability of the system is the next section of the framework to be described (see Figure 37). Although the theory of system decomposability has been discussed in detail previously, this section will give further guidance on how the system can be decomposed[25].

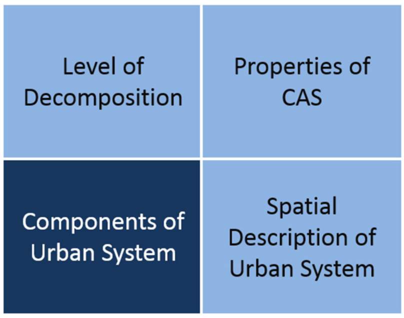

Figure 37: Level of decomposition of the system as a component of the

According to Holland (2012, p. 17), it is always best to use the lowest level of decomposition possible and the "lowest level is typically chosen as a set of easily distinguishable components relevant to a question of interest". The selection of the level of decomposition should be determined by a specific research question for the selected area, i.e. '*what is the functional response diversity of*

[25] Decomposability differs from reductionism. Reductionism breaks up a system into its component parts, and then sees each individual part as an isolated and separate from of the whole. Decomposability, on the other hand, looks at where natural boundaries within subsystems form (this is typically where the connections between components is strongest for that part of the system, i.e. within a neighbourhood) and partially isolates that part of the system for study, while still acknowledging that that subsystem is part of a larger system with which it is still interacting (Holland, 2012; Ostrom, 2007).

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the retail sector within the selected area'? To answer this question, the system will have to be broken down to an appropriate level. For this example, the level of decomposition could be:

Urban System >> Economic sub-system >> Retail

The lowest levels of decomposition may also be further decomposed into lower level components, which in turn may be still further decomposed. An inappropriate level of decomposition may make it difficult to answer the specified research question (Holland, 2012, p. 17). An example of an inappropriate level of decomposition may be using the same question as in the previous example and breaking the system down to:

Urban System >> Economic sub-system >> Retail >> type of retail activity>>size of store>>product

This is where having boundaries in their various forms becomes important as they limit the level of decomposition. The selected level of decomposition may also help in formulating the initial boundaries (Cilliers, 2005b; Holland, 2012).

To summarize, the first three parts that make up the urban system description framework (USDF) are (a) identifying how the CAS properties of the urban system present themselves. This is followed by (b) identifying the components of the urban system relevant to the study. This process will be guided by (c) an appropriate level of decomposition. The USDF has been visualised in Figure 38 which also shows how the contents (data to be identified) for the USDF can be structured.

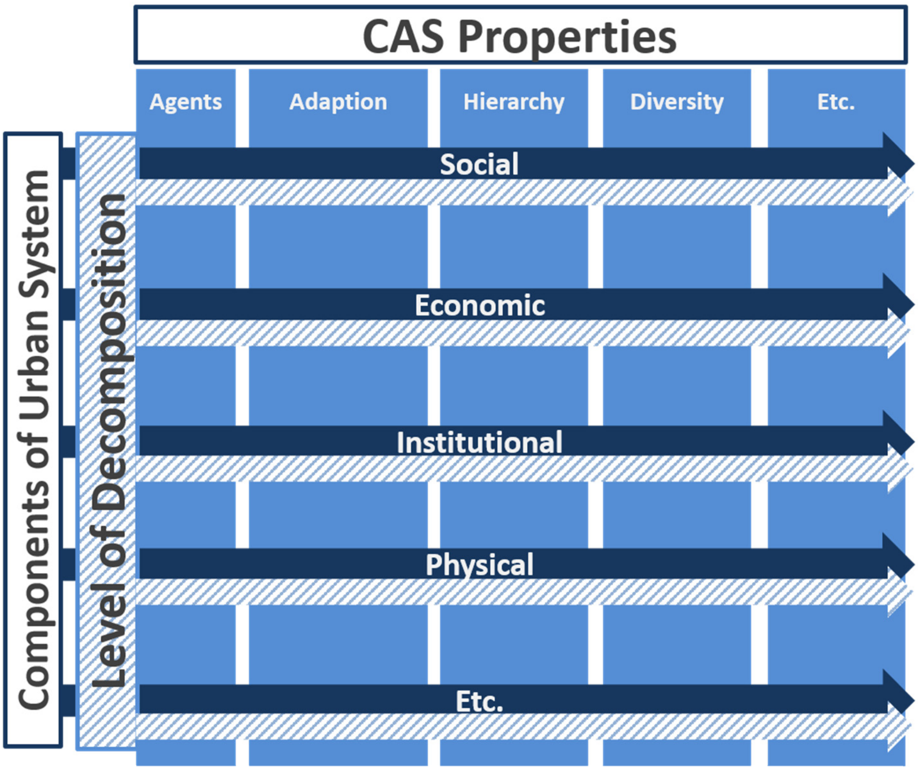

Figure 38: Visualised representation of the UDF (without spatial component)

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In the framework, the properties of the system are identified for each of the components of the urban system. These are then cross referenced with each other to see where there are similarities and differences within the identified properties of the system.

An example may be if two or more separate studies of the same spatial and temporal boundaries look at a particular system from very different perspectives (i.e. from an economic, environmental or social perspective). Although the studies look at the system from different perspectives, they may identify the same or similar agents, adaptions, etc. within the system for that particular time and space, this has been illustrated in Figure 39.

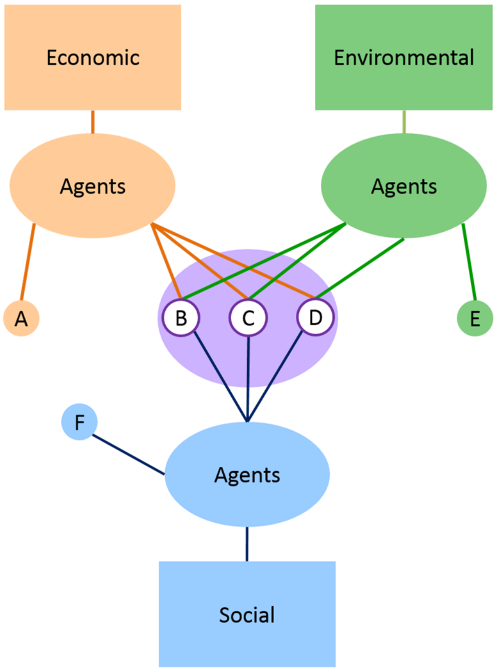

Figure 39: Potential overlap of agents identified in different studies of the same system.

It should also be noted that, because of the complementary law in systems which "suggests that any two different perspectives (or models) about a system will reveal truths regarding that system that are neither entirely independent nor entirely compatible" (Richardson, 2004a, p. 76), some discrepancies in the USDF might occur. However, by using the properties of CAS as the tool to filter and provide a common language to describe the system (even though different parts of the system are being studied from different perspectives), it is hoped that these discrepancies and incompatibilities can be minimised.

An example of the application of this framework has been provided in Table 10[26]. For this example, Lyttelton was used during the time period of 1990 - 2001. The level of decomposition has been limited to encompass only the social sub-system.

Although only basic descriptions have been given in the example, the table provides a general outline of the social sub-system during that particular time period. More detail can be added as and where needed.

[26] As noted previously the original study, Nel (2011), focused on identifying the drivers of spatial change. As a result the description of the social subsystem in Table 10 tends to be focused on spatial aspects within the subsystem.

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Table 10: A description of the social sub-system of Lyttelton between 1990 and 2001. All data sourced from Nel (2011).

Urban System Description Framework		
Area of Study:	Lyttelton	
Time period:	1990 - 2001	
Component/sub-system:	Social Sub-system	
Description of System		
Property of CAS	**Observation**	**Notes**
Agents	Home owners association	
	General public	
	School children	
	Households	
	Government (Local and national)	
	Businesses	
Adaption	Changes in population size	There was a general growth in population in this area. This was also seen in the increased amount of sub-divisions within the area to accommodate the larger population
	Changes in household size	Average house hold size increased from 2.8 in 1990 to 3.1 in 2001.
Hierarchy	Subdivisions (spatial distribution)	
	Neighbourhood sits within the larger city	
Diversity	Population diversity	Changes in the diversity and composition of the population were largely due to the abolishment of apartheid policy
	Different housing typologies	
	Income diversity	
Flows	New telecommunication technology	
	Movement of people, gods and services within system	
Self-organisation and Emergence	Location and distribution of residence and business within area	
Redundancy	More than one school	
	Different housing options	
General Notes and changes for this time period		
• The development of the retirement homes in Lyttelton Manor and Lyttelton Agricultural Holdings (Die Hoewes) allowed for Lyttelton to receive new, younger, families, due to the fact that the elderly had now moved to retirement homes. • From 1992 till 2010/1 Lyttelton saw more changes in the use of land than in previous years. • During the 1998-2000 IDP (Integrated Development Plan), the public participation process undertaken for the area was used as a means to apply pressure on the council to stop development within certain areas in Lyttelton. • A major factor that must be noted during this period was the abolishment of apartheid policy which allowed for the mixing of racial groups and brought about major changes in the structure and composition of the population within the area		

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4.4. Spatial description of the urban system

The properties and characteristics of CAS and how they appear in the urban system have been discussed in the previous section. However, one of the key aspects that is quite often missing in discussions about CAS is how these properties and characteristics present themselves in space (Roggema, 2012). This section will attempt to make the link between the abstract and the spatial by looking at what the spatial properties of CAS are. This will lead us to ask how the urban system can be described spatially, as shown in Figure 40.

We make the assumption that the spatial dimension forms part of the environment and we cannot look at complex systems without considering the environment in which they exist (Cilliers, 1998; Holland, 1996). As such, the spatial description of the urban environment also forms part of the description of the environment in which the system finds itself. Salat (2013) argues that the environment in which the system is located influences the system's behaviour, just as the system's environment reflects much of what is happening, or has happened, in the system. This description is similar to that of co-evolution, described in Chapter Two. Based on this argument, it is important to look at the environment within which the system is located, as it may tell us something about the system that might otherwise not be seen if we excluded it.

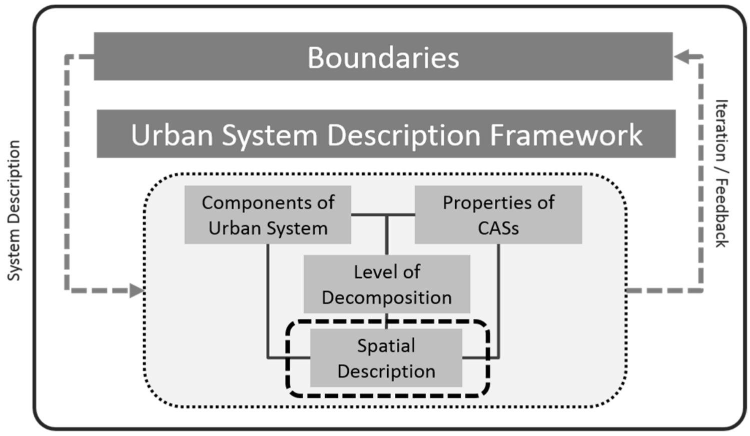

Figure 40: Spatial Link of USDF

4.4.1. How are CAS translated into space?

Urban systems are located within space. It is, therefore, reasonable to assume that some of the properties of an urban system can be seen spatially. Roggema (2012, pp. 197–200) describes how some of the properties of a CAS can be translated into the spatial dimension, as shown in Table 11. From his work, several spatial elements of urban CAS have been identified. These are: "a mix of functions, a mosaic in the city and the landscape, space for natural resources, space that has not been allocated (free space), dense and connected networks, focal points (nodes) and changing land use" (Roggema, 2012, p. 197). However, due to the nature of Roggema's (2012) work, that of adaption to climate change, only the most relevant sections will be discussed in the text below.

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Table 11: Properties of complex adaptive systems and how they appear in the spatial dimension. Taken from Roggema (2012, p. 198)

<table>
<tr><th colspan="2">Properties of Complex Adaptive Systems</th><th>Spatial Dimensions</th></tr>
<tr><td rowspan="6">Adaptive capacity</td><td>Diversity</td><td>Mix of functions</td></tr>
<tr><td>Flexibility</td><td rowspan="2">Mosaic in city and landscape</td></tr>
<tr><td>Heterogeneity</td></tr>
<tr><td>Reconfiguring</td><td rowspan="3">Space for natural resources</td></tr>
<tr><td>Balance</td></tr>
<tr><td>Learning/storing</td></tr>
<tr><td>Adaptive mimicry</td><td>Reproduction</td><td rowspan="2">Create free space</td></tr>
<tr><td>Self-organisation</td><td>Collective patterns</td></tr>
<tr><td>Emergence</td><td rowspan="2"></td><td rowspan="2">Networks, number and importance</td></tr>
<tr><td>Indirect collaboration</td></tr>
<tr><td>Large number of individual elements</td><td>Quality and quantity of connections</td><td rowspan="5">Starting points, focal points</td></tr>
<tr><td rowspan="3">Interactions</td><td>Jumps</td></tr>
<tr><td>Jets patronising</td></tr>
<tr><td rowspan="3">Tipping points</td></tr>
<tr><td rowspan="2">Undergo change and retain basic features</td></tr>
<tr><td>Change in land-use, functions, human activities</td></tr>
</table>

A mix of functions is derived from the CAS property of diversity. This contributes to a CAS's adaptive capacity. Spatially, this means, according to Roggema (2012, p. 198), when functions (such as commerce, industrial and residential space) tend to combine and mix together within a space, there is a higher diversity of functions. This also leads to a more intense use of space as the functions are located within close proximity to each other. In the urban area we can argue that this can be seen in the location and mix of things like land uses, transportation routes, economic activities, etc. (Talen, 2008, 2006)

A mosaic in the city and landscape refers to the flexibility and heterogeneity of an area, and is linked to a mix of functions (Roggema, 2012, p. 198). A mosaic in the city and landscape refers to a mix of the scales of spaces and entities within in them. In other words, we can say that it refers to the spatial distribution of places in terms of their size. For example, the size of erven, houses, parks. Roggema (2012, p. 199) argues that it is more beneficial for an area to have a mixture of different sized places and functions. This is because, in areas where a mosaic of spaces occurs, rapid, albeit temporary, changes are possible. In areas where there is no mosaic of spaces, i.e. in mono-functional spaces, like areas of extensive urban sprawl in a city, for example, change is possible near the edges, but it is difficult to change the entire space (Roggema, 2012, p. 198). The mosaic of the city that Roggema (2012) describes can also be viewed as the spatial distribution of objects and functions of the city. This has been explored further by Bourdic et al.(2012), Salat (2011), Salat and Bourdic (2011) and Batty

(2014, 2009, 2008, 2007) who look at the spatial distribution of a city in terms of fractals as well as power laws[27].

Space for natural resources within urban areas is about creating a balance between supply and demand of natural resources (i.e. water, food and energy), which can be further improved by better means of storing such resources. This adds to a system's adaptive capacity by creating buffers or reserves of resources (redundancies) that can be redistributed when needed (Roggema, 2012, p. 199).

Space that has not been allocated (free space) refers to land, or buildings, for example, that has no clearly defined use or activity taking place on it. This can also include areas that have fallen into disrepair (Roggema, 2012, p. 199). Roggema (2012, p. 199) reasons that, by having open unused spaces, the system is free to use these spaces in a way that best suits it. This allows for a recycling of resources, in this case repurposing land or buildings, and allowing the system to use its resources more efficiently.

The number and importance of networks is the next aspect of CAS that can be seen spatially. This aspect links with the properties of interactions and flows that were discussed in Chapter 2. Roggema (2012, p. 199) states that, when there are "more connections of better quality (faster, higher connectedness, more links, more intense) indirect collaboration between existing elements in the network/in the area will facilitate emergent patterns and functionalities". Roggema (2012, p. 199) suggests that networks such as water, energy, communications and transportation can be looked at spatially. The latter (transportation) has been looked at in various ways by many authors, (for detail on this see Bourdic et al.(2012) (urban morphology), Salat (2011) (urban morphology), Salat and Bourdic (2011) (urban morphology), Crucitti et al. (2006), Frank et al. (2006) (urban morphology), Cardillo et al. (2006) (urban morphology and graph theory), Porta (2001), Porta et al. (2005) (graph theory), Porta et al (2006b) (graph theory), Porta et al (2008) (graph theory) and Marshall (2005) (urban morphology and graph theory)).

Linked to the network are focal points. These are located at important meeting points of the network and are where the connections tend be the strongest and/or most numerous. Figure 41 shows an example of this by illustrating a random network where some nodes are better connected than others. Change within the system is most likely to happen at these points, as there is a greater opportunity for chance interactions to occur (Roggema, 2012, pp. 199–200). This is similar to the chance encounters on sidewalks that are described by Jane Jacobs (1961, chap. 2). Roggema (2012, p. 200) provides the following spatial examples of focal points:

Figure 41: A network showing the various connetions between nodes. The darker and larger the node the more 'central' and better connected it is.

[27] Power laws, also called Zipf's law, have been discussed in detail in Chapter 2.

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"crossroads, intersections, bridges, dams, river deltas, public squares, energy distribution hubs, communication hubs, airports, shopping centres".

The final aspect that Roggema (2012, p. 200) describes is the potential for changes in land use and human activities. The potential within a system for functions and activities to adapt is one of the factors that allows the system to change.

Thanks to the explanation by Roggema (2012), the properties of CAS can be translated into the spatial dimension with particular emphasis on the urban system. This can be done by considering (a) the various functions of the system being observed (i.e. commerce, industry and residential space). (b) That the urban system is comprised of a mixture of elements that are distributed spatially, are of various sizes, on different scales, and have different functions. Included in these is lack of function or use. These unused or disregarded elements can provide an opportunity for the system to rejuvenate some areas, while others decline in an ongoing process. Additionally, Roggema (2012) emphasizes that (c) the quality and number of connections within the system are important as nodes within the network are the most likely place for change to occur because there is a greater possibility of chance encounters at those nodes. Lastly (d) the property of adaptation can be seen spatially though changes in land use and human activity. Roggema (2012, p. 200) emphasizes that these "spatial dimensions need to be seen as mutually complementary and form an integrated part of each particular area. Each of the dimensions is strongly related to the other ones". If what Roggema (2012, p. 200) states is to be taken to heart, then any description of the urban system must look not only at how these spatial dimensions present themselves, but also how they work together. By using the description provided above as a guide, it is possible to begin to spatially describe not only a CAS but also the urban system.

While the approach of some authors to studying CAS spatially, and specifically the city, is to use computer simulations (Batty, 2007; O'Sullivan, 2004, p. 282; O'Sullivan et al., 2006, p. 611; Roggema, 2012, p. 102), other authors such as Bourdic et al.(2012), Marshall (2005), Neal (2013) and Salat (2011) provide us with alternative tools and methods that can be used to describe the spatial properties outlined above. The section to follow will describe some of the methods available.

4.4.2. Urban spatial description

The previous section discussed how the properties of CAS can be translated into the spatial dimension particularly within the urban system. This section seeks to provide a means to describe the spatial properties by presenting a series of tools, methods and indicators. These descriptions have been largely based on the work of Bourdic et al.(2012), Marshall (2005) and Salat (2011). Each of the spatial properties identified by Roggema (2012) will be presented with a means to describe it spatially after which an example from Lyttelton and Irene will be given. The aim of this section is not to present tools to analyse the spatial component of the urban system. Rather, it seeks to highlight the possibility of doing so and the methods presented as a possible way of doing this.

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4.4.2.1. Mix of functions

The first spatial dimension to be explored will be *Mix of functions*. Roggema (2012, p. 198) gives examples of some functions (i.e. commerce, industry and residential space). Dempsey et al. (2010) provide a set of indicators that can be used to identify and measure land use[28]. These indicators typically describe the various land uses in an area and can be easily identified by reviewing the zoning and or land use activities in an area. This has been done for Irene and Lyttelton and is shown in Figure 42[29] (Zoning 2013) and Figure 43 (land use 2011). Linked to this is the spatial property of free spaces. These, as Roggema (2012, p. 199) points out, can be vacant land and buildings, or any unused or under used spaces. The vacant land within Irene and Lyttelton have been shown in Figure 43

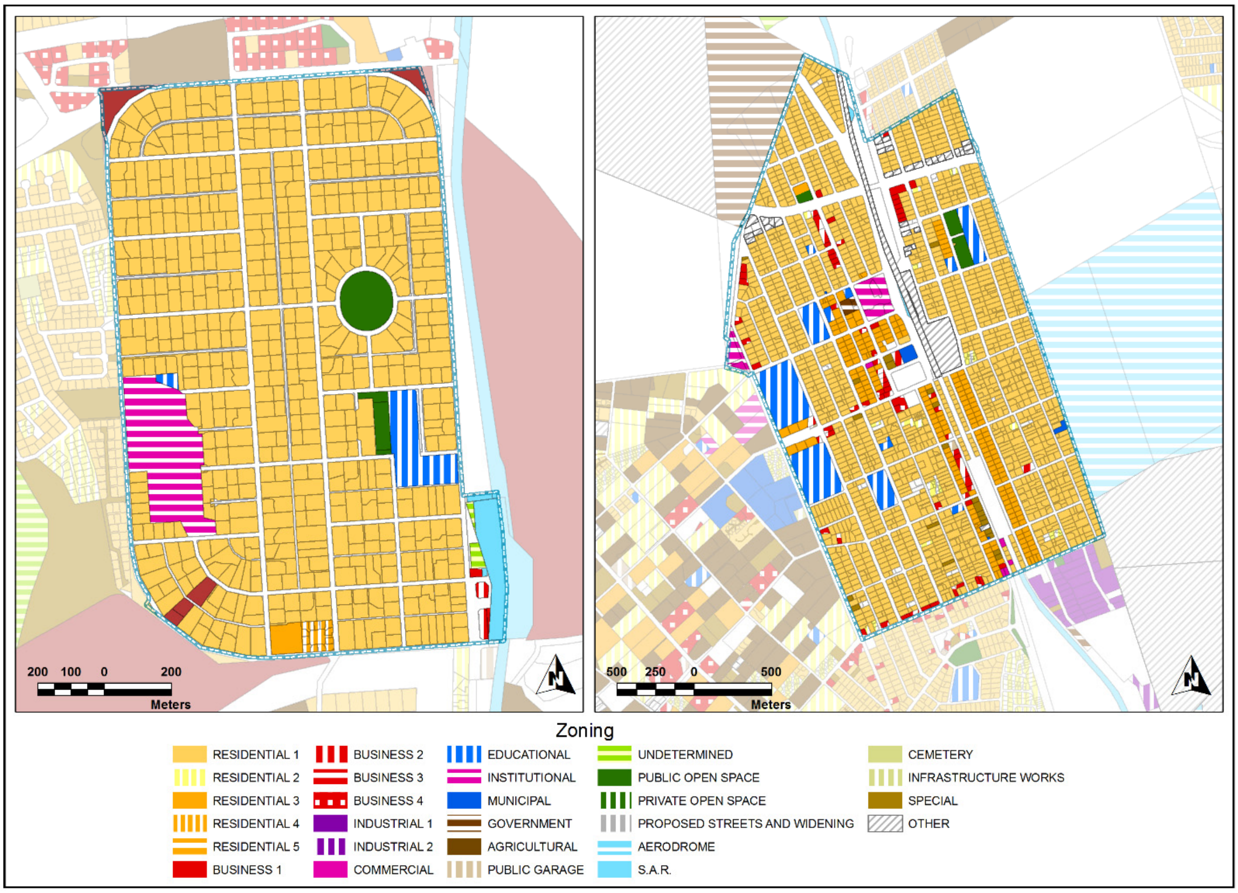

Figure 42: Zoning of Irene (left) and Lyttelton (right). Data source: City of Tshwane (2013)

[28] Dempsey et al. (2010) provide several indicators for measuring and describing the element of urban form. These have been included in Annexure 6.
[29] Larger maps can be seen in Annexure 5

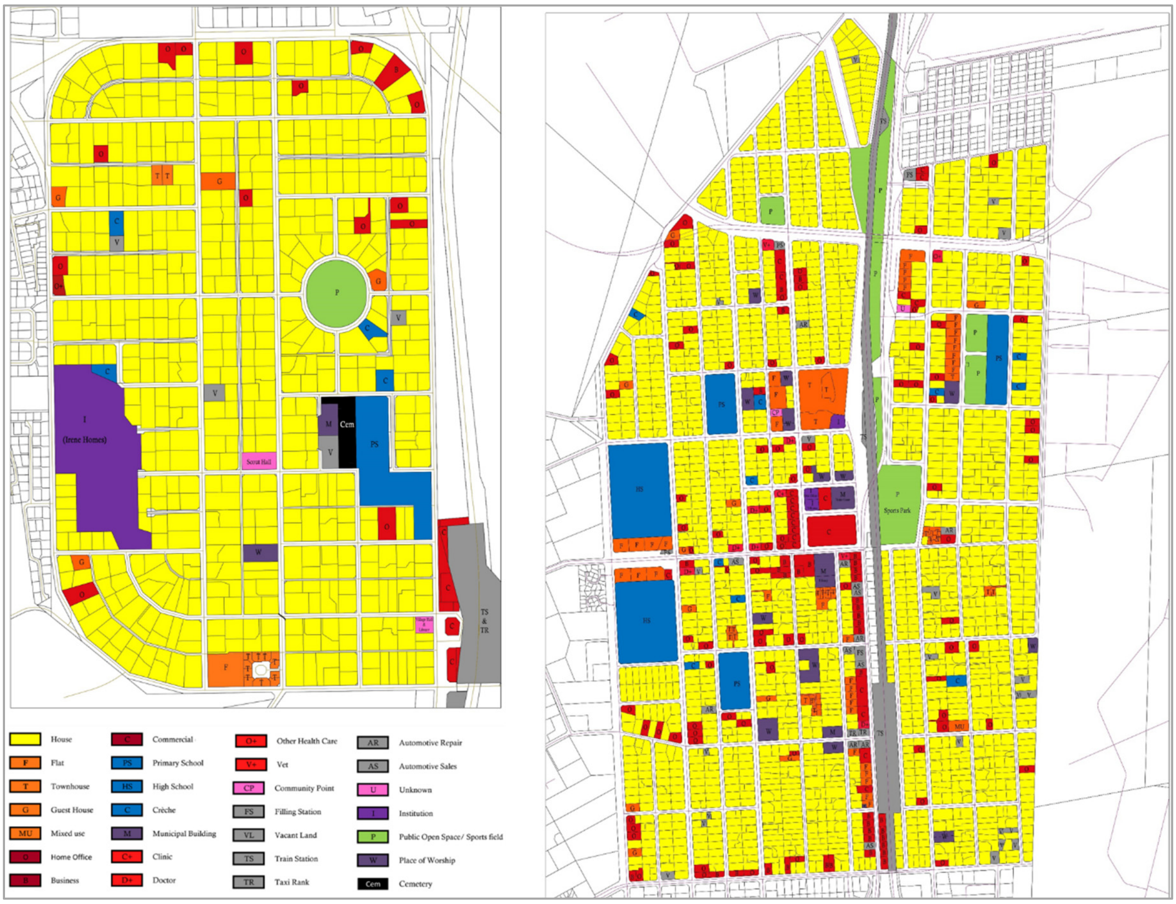

Figure 43: Land use of Irene (left) and Lyttelton (right) in 2011. Image source (2011)

4.4.2.2. Mosaic in city and landscape

From the above discussion, we know that the spatial property of *Mosaic in city and landscape* can be translated as the spatial distribution of elements of the urban system. Salat (2011, p. 66) outlines spatial distribution of elements as a universal law for the distribution of urban elements/objects of different sizes and at different scales. Spatial distribution can be defined as the "relative concentration or dispersion of objects on a given scale compared with all known objects on a bigger scale" (Bourdic et al., 2012, p. 595). Salat (2011, p. 67) shows that the spatial distribution of elements within the urban system follows power law distributions in terms of their relative size and the number of elements of that size. This echoes the description in chapter two of Zipf's law for the size and rank of cities which has been investigated by Barabási and Bonabeau (2003), Batty (2014, 2008, 2007), Crumley (1995) and Pumain (2012).

Salat (2011) illustrates how well-functioning and complex areas of cities abide by power law distributions. Salat (2011, pp. 79–82) shows this by using the example of how urban subdivisions follow a power law distribution and older, more spatially complex, areas tend to have a more spatially equitable distribution of urban subdivisions. In other words, there should be an inverse relationship between the size and the number of land parcels: the larger the land area the fewer parcels of land there should be of the same or similar size (Salat, 2011, p. 66). Similarly, Batty (2008) shows that the same is true for buildings and population densities. While Neal (2013, p. 76), Salat and Bourdic (2012a) and Scellato et al. (2006) show that the transportation network, in the form of road hierarchies, street intersections, etc., can also be described by using power laws.

The spatial distribution of land subdivisions was examined for Irene and Lyttelton and is shown in Figure 44. The calculation was done by ranking the land parcels according to their size (area), after which the Log for both the rank and size was determined. The results of $R^2 = 0.7603$ for Lyttelton and $R^2 = 0.8518$ for Irene suggest that both areas, although not bad, do not have a very equitable spatial distribution of land subdivisions (the ideal being $R^2 = 1$). The reason for these two sets of results could be due to a few factors. The first being sampling error and human error in the calculations. The second could be the result of external forces (i.e. restrictions on the minimum size of the land which is a known factor in these two areas).

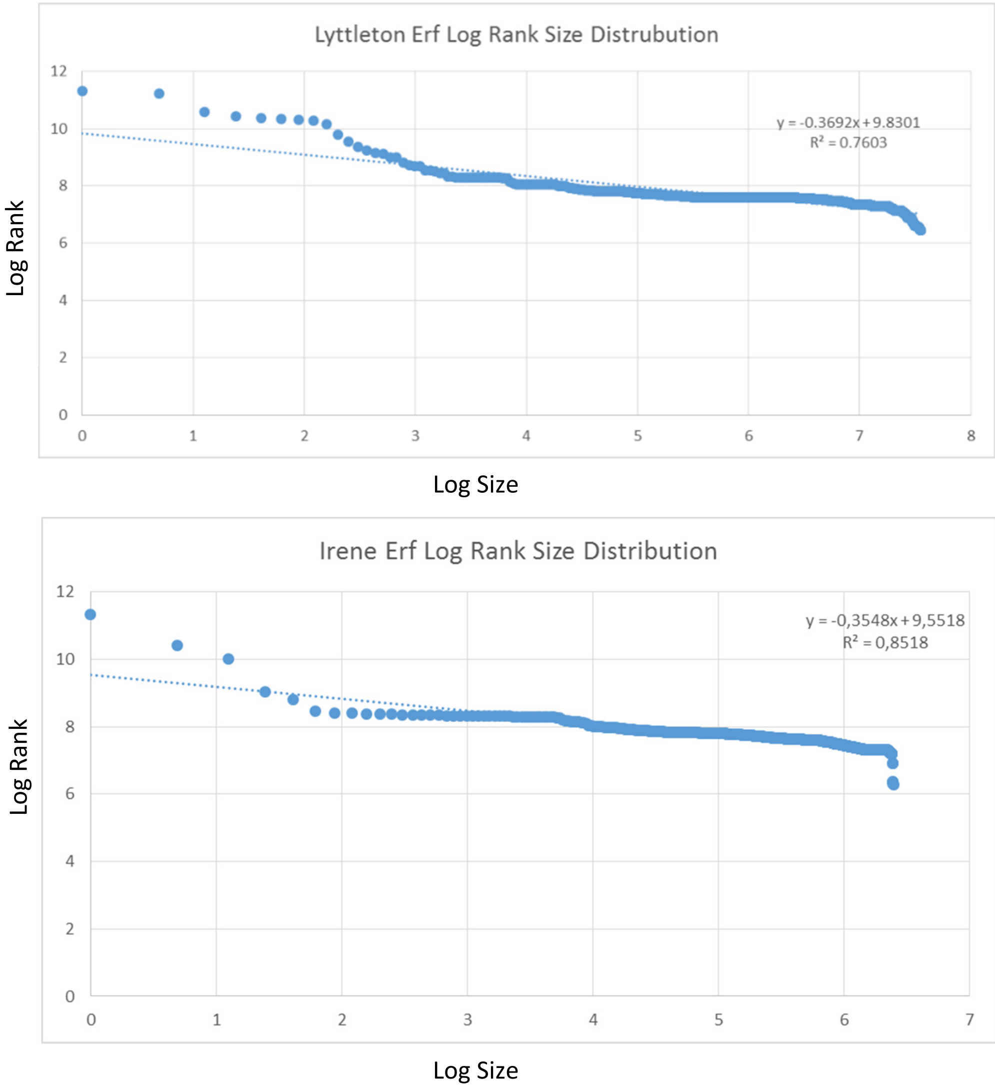

Figure 44: Power law distribution of land parcels for Lyttelton (top) and Irene (bottom).

4.4.2.3. Networks and focal points

There are many different types of networks (i.e. water, human and natural, energy, communication, etc.) that can be found within the urban system (Roggema, 2012, p. 199). However, the one that is studied the most is probably the transportation network. There are many different methods of studying, describing and measuring the transportation network (see Berryman et al.(2011), Calgary Regional Partnership (2011), Cardillo et al. (2006), Dalton et al. (2012), Hillier (2012), Jiang (2009, 2007), Jiang and Claramunt (2004), Kühnert et al. (2006), Porta (2001), Porta et al. (2006b) and Scellato et al. (2006)), but only a select few will be discussed below.

Network connectivity can be studied by examining the components of the network, nodes and links, and the way they are configured (Hein et al., 2006; Neal, 2013). For the transportation network, the road network in particular, this is done by looking at street intersections/junctions (nodes) and the lengths of street that link them to each other (links) (Marshall, 2005, p. 88; Salat, 2011, p. 243).

Connectivity is measured by examining the number and ratio of links and nodes, the distances between them and their configuration. The higher the density of intersections within a network or along a given path, the better connected the neighbourhood or path is and the more likely the distances between the intersections will be shorter (Landman and Nel, 2014, p. 4; Marshall, 2005, p. 86; Salat, 2011, p. 216). Table 12 contains a list of different measures and indicators for connectivity of a network, while Table 13 gives the results of these indicators when applied to Irene and Lyttelton.

Table 12: Indicators for connectivity

Name	Description	Formula	Source
Intersection Density (Nodes per km²)	Measured as the number of intersections per km² land	$\frac{No.of\ Interscetion}{Area\ (km^2)}$	(Bourdic et al., 2012, p. 598; Salat, 2011, p. 242; UN-Habitat, 2013, p. 42)
Street Density (Links per km²)	Measured as the total length of linear km of streets per km² land	$\frac{Tot.length\ of\ streets}{Area\ (km^2)}$	
Link-to-Node Ratio	This is the number of links divided by the number of intersections. A higher ratio implies higher street connectivity	$\frac{No.of\ links}{No.\ of\ nodes}$	(UN-Habitat, 2013, p. 42)
Connected Node Ratio	Number of intersections divided by the number of intersections plus cul-de-sacs. The maximum value is 1.0. Higher value indicates that there are relatively few cul-de-sacs. This implies a higher level of connectivity.	$\frac{No.of\ nodes}{No.\ of\ nodes + cul - de - sacs}$	

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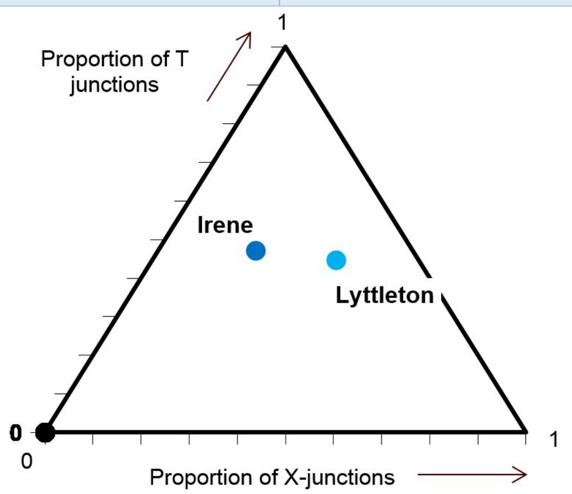
Intersection composition (X and T-Junctions and cul-de-sac)	Measures the ratio of X and T-Junctions and cul-de-sacs to the total number of intersections. A higher ratio of X-junctions indicates a more open network.	$\frac{No\ of\ X-junctions}{No.\ of\ nodes}$ $\frac{No\ of\ T-junctions}{No.\ of\ nodes}$ $\frac{No\ of\ cul-de-sacs}{No.\ of\ nodes}$	(Marshall, 2005, p. 96)
Average distance between intersections	Mean value of the selection of the length of links between two intersections	$\frac{Sum\ length\ of\ links}{No. of\ links\ between\ nodes}$	(Bourdic et al., 2012, p. 598; Salat, 2011, p. 242; UN-Habitat, 2013, p. 42)
Cyclomatic number per km²	Measures the number of independent circuits in the road network per km². The higher the ratio the more possible routes there are within the network	$\frac{L - N + 1}{Area}$ (L: number of links; N: number of nodes)	(Bourdic et al., 2012, p. 600; Salat, 2011, p. 243)

Table 13 shows the results of the different measures of connectivity for the two neighbourhoods. The results show that, in some cases, Irene scores better than Lyttelton, but the overall result is that Lyttelton is better connected than Irene.

Table 13: Connectivity of Irene and Lyttelton

Indicator	Irene	Lyttelton
Intersection Density (Nodes per km²)	51	30
Street Density (Links per km²)	71.8	47
Link-to-Node Ratio	1.40	1.54
Connected Node Ratio	0.754	0.901
Intersection composition (X-Junctions)	20.2%	38.2%
Intersection composition (T-Junctions)	47.2%	44.7%
Intersection composition (cul-de-sac)	32.6%	17.1
Nodegram, developed by Marshall (2005, p. 96), showing the relative proportions of X- Junctions, T-Junctions and cul-de-sac's for Irene and Lyttelton.		
Average distance between intersections (m)	188.8	226.2
Cyclomatic number per km²	20.69	16.73

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4.4.2.4. Change in land-use, functions, human activities

As the name suggests, this property can be seen spatially when looking at changes within an area over time. This property identifies how the system adapts spatially. The typical aspects to be looked at are changes in land use (i.e. re-zoning), in the function provided in an area, and in human activity (i.e. demographic changes). The example in Figure 45[30] shows how the land in Irene and Lyttelton has been subdivided from 1970. These changes are even more evident when looking at the changes in land use. Table 14 shows the changes in land use for Irene and Lyttelton from 1956 to 2011. Nel (2011, p. 65) talks about these changes (or lack thereof) reflecting some of the preferences of the occupants and the resultant dynamics within these two areas.

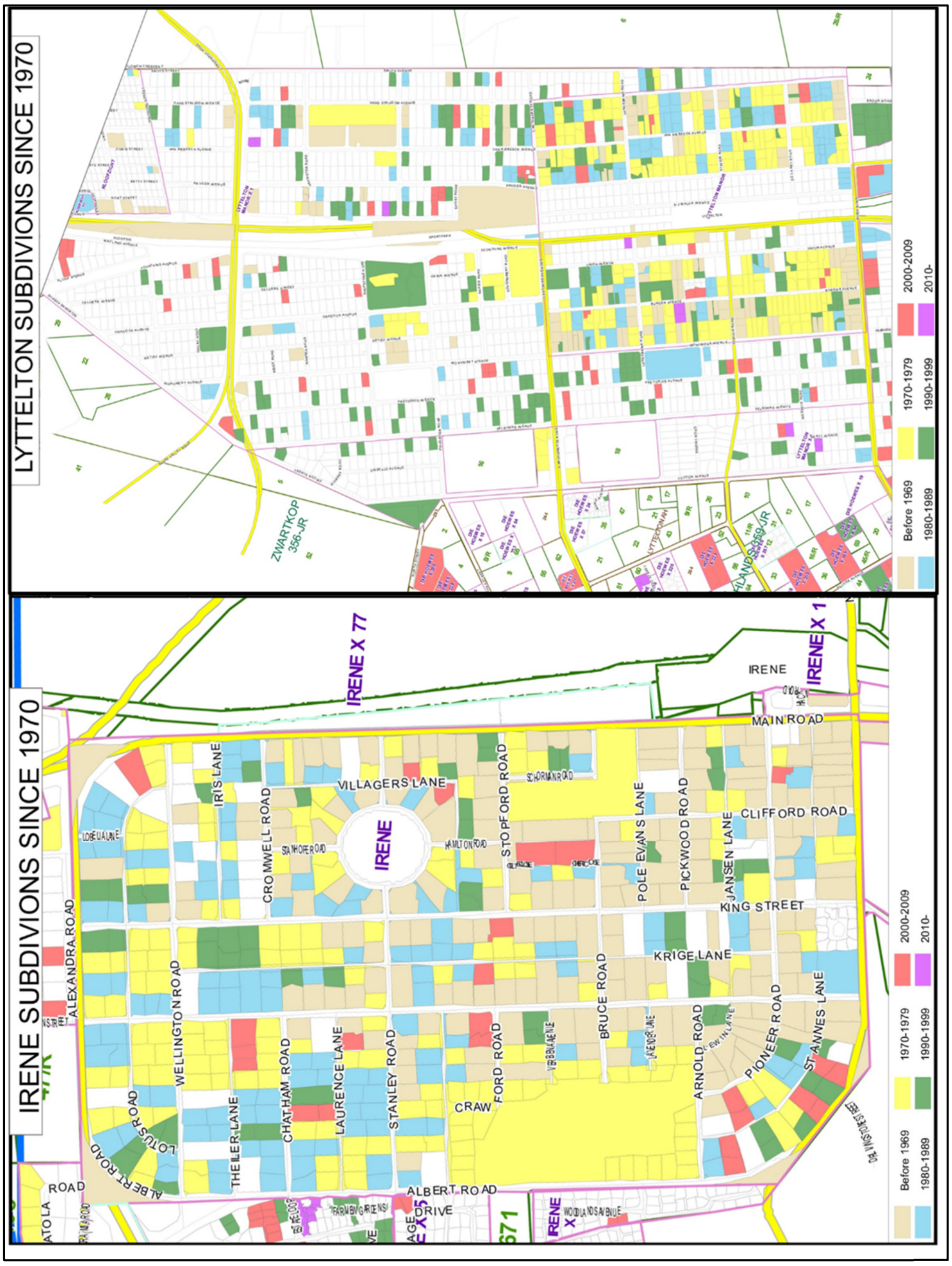

Figure 45: Location of subdivisions in Irene (bottom) and Lyttelton (top) from 1970 to 2011

[30] Larger images can be seen in Annexure 5

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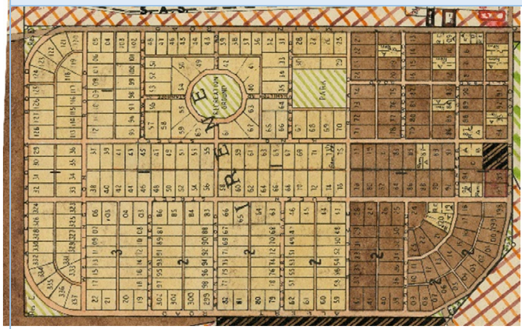
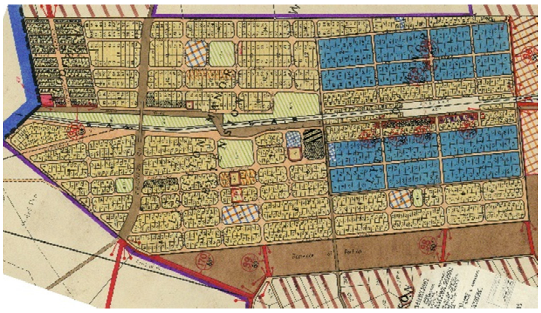
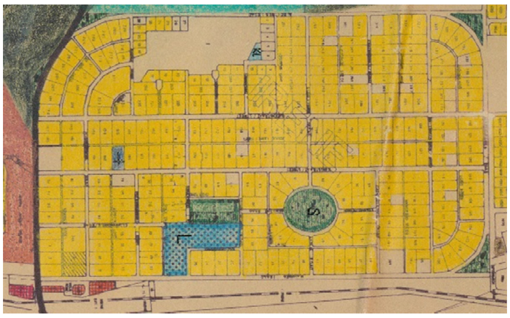
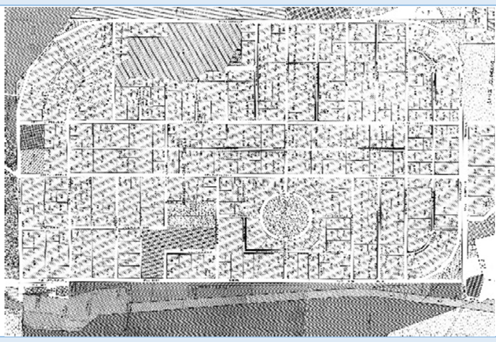
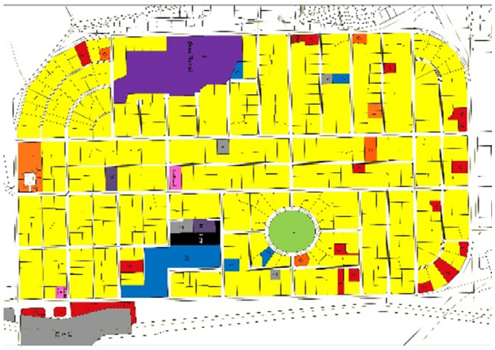
Table 14[31]: Changes in land use for Irene and Lyttelton from 1959 to 2011. Source Nel (2011)

Irene changes in land use	Lyttelton changes in land use
1959	
	
1976	
	
1992	
	
2011	
	

[31] Larger images can be seen in Annexure 5

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Carmona et al. (2003, pp. 61 – 66) and Carmona and Tiesdell (2007) describe various morphological aspects of the city; namely land use, buildings, plot subdivision and street patterns; changing at different speeds and for different reasons. This suggests that some aspects are more resistant to change, i.e. street patterns, than others, i.e. land use. Based on work by Carmona et al. (2003) and Carmona and Tiesdell (2007), the changes and frequency of changes identified (i.e. changes in Land use) within Irene and Lyttelton are not entirely unexpected. Table 15 describes the expected speed or frequency of change for the identified morphological aspects under consideration and indicates if these changes have taken place within the two case study areas. Table 15 shows that both Irene and Lyttelton have experienced changes in all aspects. However, the street patterns have only experienced some small changes.

Table 15: Morphological change. Source Carmona et al. (2003, pp. 61 – 66) and Carmona and Tiesdell (2007)

Speed of change	Morphological change	Seen in case studies
Fast	Land use	Yes
Medium	Building	Yes
Slow	Plot/erf subdivision	Yes
Very Slow	Street pattern	Slight changes in both

4.5. Urban described

This chapter started off by presenting a series of questions that needed to be answered in order to describe the urban system and how it changes. The first of these centred on the issue of system boundaries. This was addressed by reviewing several discussions on boundaries and making the case that the question being asked largely determines the boundaries that are placed. From there, three types of boundaries were suggested; spatial, temporal and intangible; for use in any study seeking to describe the urban system.

The second question sought to identify the key components of the system and the fact that it is not easy to answer this question. A framework was developed to identity the key components of the system. The criteria for such a framework were explored, after which the framework itself was presented. The framework suggested that it is possible to describe the urban system by identifying the CAS properties and how they present themselves in the system being studied. Furthermore, it suggested that further clarity into the system could be gained by breaking the system down (decomposing) into smaller manageable pieces guided by the research question. From there, it is possible to identify the key components of the system, taking into account whatever is not included should be seen as part of the environment and can also not be completely ignored (Reif, 1973, p. 29). As the last part of the framework, the spatial dimension was included. This described how the properties of CAS can be translated and described spatially. Several tools that can be used were

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presented to describe the system spatially. Examples of these include a study of the connectivity of the urban network, the changes in land use, and the spatial distribution of land.

The third question that was asked, how the system has changed, will be answered in the chapters to follow. This will be done by looking at why it is important to look at change, after which the study will seek to answer how change should be identified and described.

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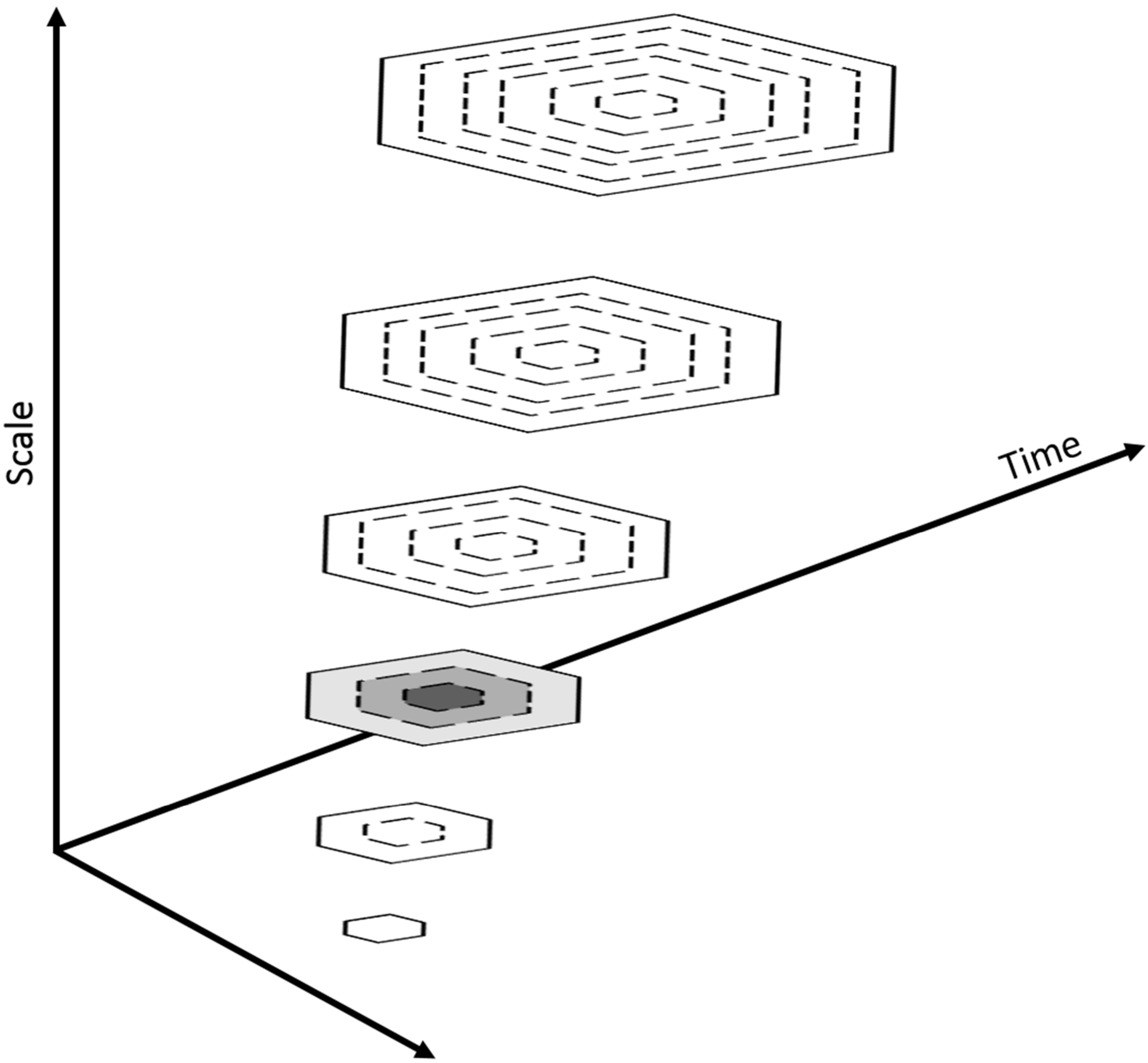
Chaper 5: A multiple of time and space



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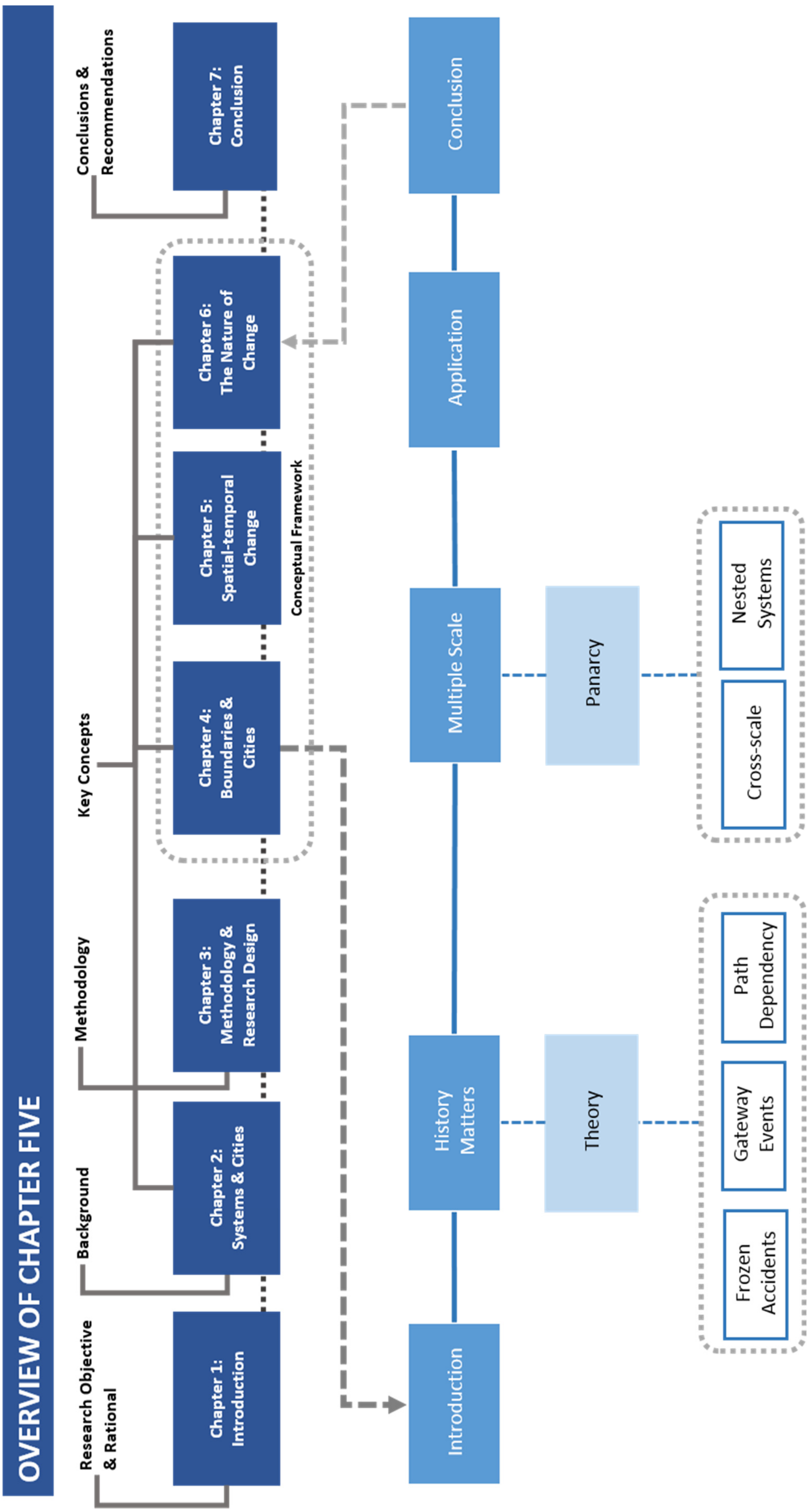

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5.1. Introduction

The previous chapter discussed the issues of setting boundaries and describing the system. The chapters to follow will present the next part of the proposed framework in an attempt to answer the question of how changes in the system can be identified and described. This chapter will be centred on the second part of the proposed framework, *change identification* (as shown in Figure 46). The first two parts of this chapter will largely comprise of a discussion on the theoretical underpinnings of why it is important to look at more than just our selected focal scale and time-frame.

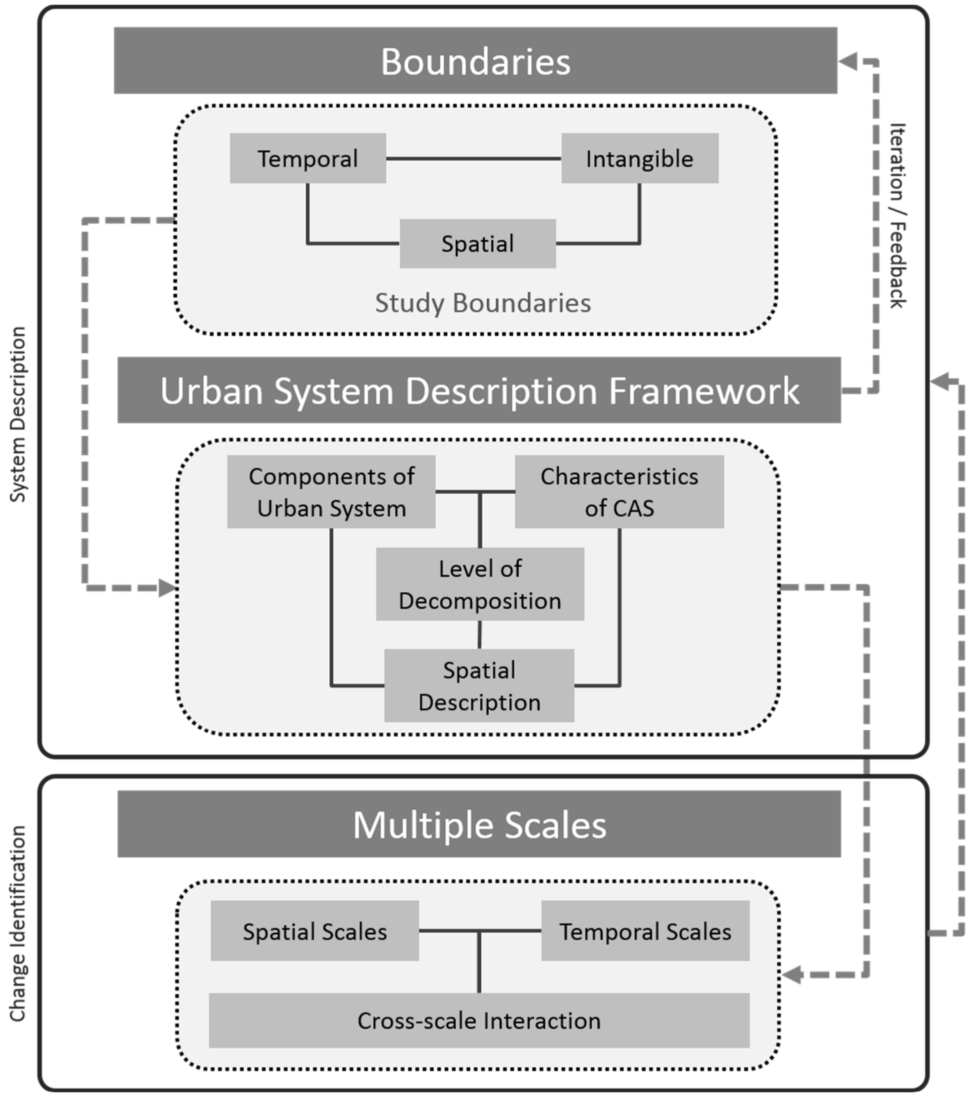

Figure 46: How the *Change Identification* Section of the Framework Fits Within the Larger Framework

In part one of this section, the importance of time and how events affect a system across time-scales will be discussed. Part two will build further on the discussion, but will focus on cross-scale interactions. The argument will be made for why we cannot understand a system's complex behaviour without taking note of its history and how the system interacts across different scales.

The third part to this chapter will bring the focus back to Irene and Lyttelton, and illustrate how these concepts can be used to begin identifying change within a system by identifying frozen accidents and gateway events that can lead a system onto a particular path dependency.

5.2. History matters: frozen accidents, gateway events and path dependency

"Complex systems have a history. Not only do they evolve though time, but their past is co-responsible for their present behaviour. Any analysis of complex systems that ignores the dimension of time is incomplete, or at most a synchronic snapshot of a diachronic process"

(Cilliers, 1998, p. 4)

As complex systems are, by their very nature, dynamic and constantly changing, we cannot ignore the fact that systems have history and that their histories have an impact on their current and future behaviour. To understand systems and their complex behaviours, we must study them, not only in the present, but also their past (Cilliers, 1998; Geyer and Rihani, 2010; Gunderson and Holling, 2001).

This section describes why it is important to study a system's history. This will be done by exploring a few different concepts of how events, large and/or small, can shape and determine a system's current and possibly future behaviour and trajectory[32]. The concepts that will be discussed are frozen accidents, gateway events and path dependency.

5.2.1. Frozen accidents

CAS "change primarily through the reinforcement of [a multitude of] chance events, such as mutation and environmental variation, operating at local levels" (Levin, 1998, p. 433). These chance events are called *frozen accidents* (Gell-Mann, 1994a, p. 133; Geyer and Rihani, 2010, p. 44; Levin, 1998, p. 433). The accumulation of many events within a system form a part of the process of a system's evolution or adaption mechanisms (Glazebrook and Wallace, 2012).

Each event has outcomes or consequences that affect the system and its behaviour (Gell-Mann, 1994a, p. 133). Some outcomes may be small, barely noticeable, while others will have a greater impact on the system. An example may be an adaption by a predator to hunt a newly introduced (prey) species in an eco-system. By adapting, the predator is filling a newly created niche. This can be seen as an example of a frozen accident. If the newly introduced prey then adapts to better survive in the eco-system, by adapting to run faster to escape the predator, then this would be an example of how one frozen accident can, directly (or indirectly), lead to the creation of another. This cycle of predator-prey adaption shows how a series of frozen accidents can lead to the process of co-evolution (Holland, 2012, pp. 18–20).

After a frozen accident has occurred, that accident then integrates into and becomes part of the system. A collection of frozen accidents can keep a system on its current path (see path dependency

[32] Trajectory in this case can be seen as "a function of (not yet realised) future states" of the system (Roggema, 2012, p. 104).

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below) or set the system on a new path, through the creation of a gateway event. This has been illustrated in Figure 47: each dash represents a frozen accident that then forms part of the system. When combined, the collection of small frozen accidents have a significant effect on the system's long-term trajectory, as they move the system in a particular direction. Without a particular frozen accident, or series of accidents, the system may have had a different trajectory (grey lines shown in Figure 47).

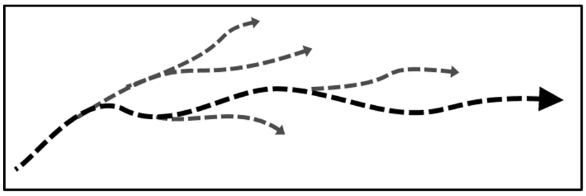

Figure 47: A representation of how a collection 'frozen accidents' sets a system on a particular path. The thick arrow represents the systems actual path while the thinner, grey, arrows are possible paths that the system could have taken.

The accumulation of frozen accidents can also lead to the creation of regularities within a system. Regularities can be seen as commonly reoccurring entities within a system that result from a large number of frozen accidents. An example of this is how a collection of frozen accidents, over many millennia, led to the evolution of the human race. Humans are now considered to be a regularity within the global system (Gell-Mann, 1994b; Geyer and Rihani, 2010).

The European Union, as an additional example, resulted from an accumulation of many frozen accidents "(chance meeting between core diplomats, unpredictable aspects of policy spillover, etc.) and entrenched regularities (the Cold War, US economic hegemony, etc.)" (Geyer and Rihani, 2010, pp. 44–45). What is typical of complex systems is the continual contest between the conservative influence of frozen accidents, keeping the system on a particular trajectory, and the adaptability of emerging regularities (Geyer and Rihani, 2010, p. 45). This contestation can be further seen in Gunderson and Holling's (2001) theory of Panarchy (discussed in more detail below). The higher, slower levels of the system, which contain the system's memory, apply constraints on the lower levels, which produce a myriad of small disturbances (through local interactions) that, on occasion, can move up to affect the higher levels of the system.

5.2.2. Gateway events

Gateway events are major events that occur from time to time and create new niches within the system as well as unexpected opportunities for some (the discovery of gold in Witwatersrand area leading to the creation of Johannesburg) and disaster for others (like the Tōhoku earthquake and tsunami that hit Japan in 2011) within the system. Gateway events are also a big contributor to the creation of punctuated equilibrium[33] (Geyer and Rihani, 2010, p. 44).

[33]Punctuated equilibrium refers to long intervals within a system of relative global stability, albeit with local energy, followed by short periods of rapid change (Geyer and Rihani, 2010, p. 44). Torus attractors provide us with an example of the global stability with local variability (see Annexure 2, Key concepts of Physical Complex systems: Local variety and global stability, for an image of this type of attractor)

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A gateway event can be, for example, a new innovation within a system. The invention of the internal combustion engine (which can be argued to have completely revolutionised the wold), and the creation of the internet, are examples of gateway events that have affected the global system. Figure 48 illustrates conceptually how a gateway event (red) may alter a system's trajectory (grey arrow) and set it on a new path (black arrow).

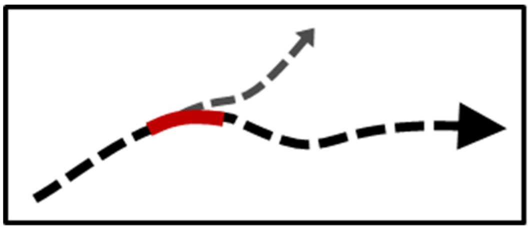

Figure 48: Illustration of gateway events changing the trajectory of a system

A "system, individual, group or nation must have sufficient variety and flexibility to survive the shock of the latest gateway event in the first instance before it could proceed to profit from the new opportunities on offer" (Geyer and Rihani, 2010, p. 45). In other words, gateway events can create a large disruption to a system and, if the system is not geared for such a shock, it may not be able to capitalise on the opportunities that the event may bring.

Understanding what has happened in the past may help us understand why current events, behaviours, patterns or norms (i.e. cultural norms that different societies may have) are prevalent. It might also be that some behaviours are repeated after a particular time period has lapsed, i.e. the seasons of the year (this can also be seen in things like fashion and architecture). Without some form of history, we have no, or very little, means of evaluating change.

5.2.3. Path dependency

Time moves in one direction only, from past through the present and into the future (Ball, 2005; Cilliers, 1998; Gell-Mann, 1995; Geyer and Rihani, 2010; Holland, 1996; Johnson, 2002; Solé, 2011). As Beinhocker (2006, p. 212) explains: "In evolutionary systems, history matters; where you can go in the future depends on where you have been in the past". A system's current and future behaviour is a product of a collection of frozen accidents and gateway events from its past (Portugali, 2010, l. 2561). A collection of frozen accidents and gateway events can set a system on a 'locked in' trajectory that is not easily altered. This locked in trajectory, or 'directional bias' of the system, is often called path dependency (Beinhocker, 2006; Levin, 1998; Martin and Sunley, 2006; Roggema, 2012).

5.2.4. Why history matters

Why is it important to consider frozen accidents, gateway events and path dependency in the study of CAS? Portugali (2010, l. 918–920) answers this by saying, "The complex system does not just develop randomly but is path-dependent, i.e. development takes place under certain conditions that can be defined and that provide insight into the system and its development". In other words, by understanding the conditions that placed the system in a particular trajectory, we may gain insights into how the system functions, a view supported by Batty (2007, p. 21). By understanding the history of a system, we may be able to identify frozen accidents, gateway events and cases of path dependency. This point is further argued by the Resilience Alliance (2010, p. 18) which states that:

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> "Understanding what is behind these changes – the change drivers – can provide insight into how the historical system dynamics have shaped the current focal system and what effects they might have in the future. A historical profile of the system can also reveal changes in the system resilience over time, including those that occur in response to specific human interventions, whether intended or not".

Knowing how events, large and small, help to shape the system and create a particular behaviour or trajectory, we take another look at the proposed framework where interactions and events across time can be added. By identifying these events, we can further expand our understanding of the system. This addition can be seen in Figure 49, where multiple USDFs have been layered on top of each other. Each USDF (layer) represents a sub-focal temporal boundary (i.e. 5 - 10 years) of the larger temporal boundary (i.e. 100 years). This is done to describe the system's short-term behaviour at various intervals. By adding these multiple short-term USDFs, it is proposed that the long-term system behaviour can be identified and described when they are combined.

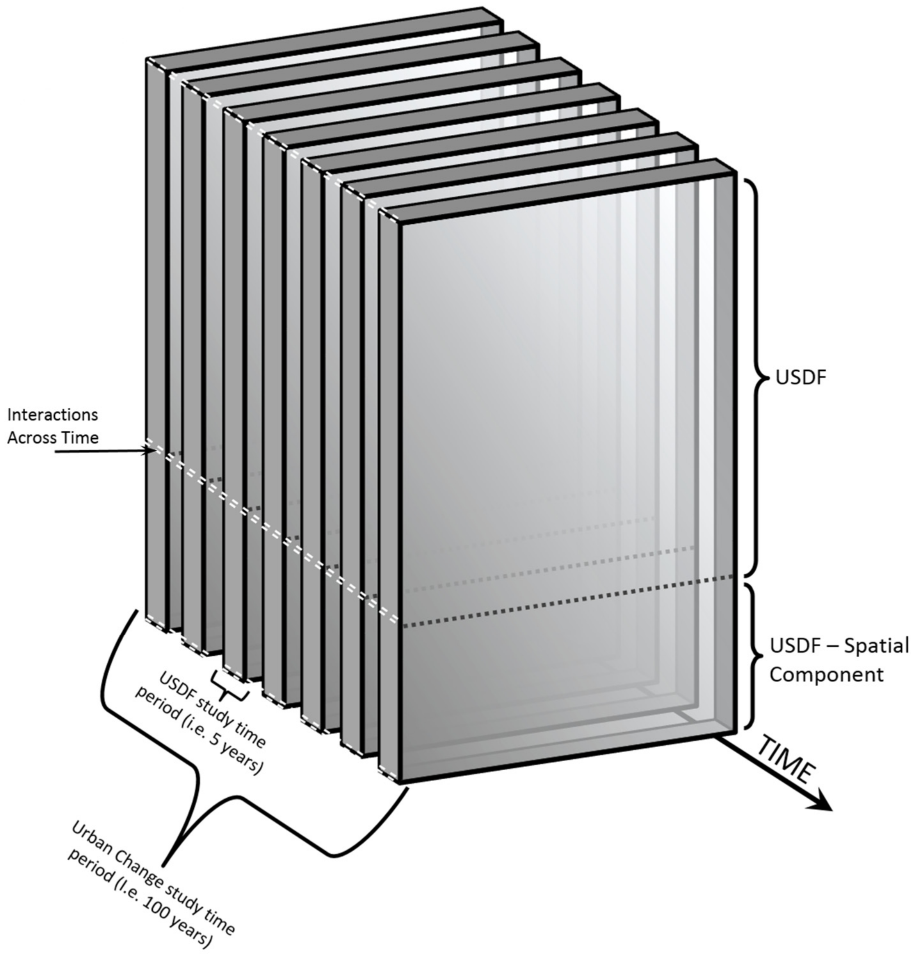

Figure 49: Addition of the interaction of time to the framework. This creates a layering of the USDF to help identify change within the system.

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By adding the component of the system's history to the study of that system, some depth of understanding can be achieved about the focal systems present. However, as the following discussion will illustrate, this still does not provide full understanding of the processes acting on the system and driving its changes. For this, we must add the component of scale to the framework.

5.3. Multiple scales

The previous section emphasised the importance of a system's history and how past events can alter the trajectory of the system. However, we should not limit ourselves to considering only interactions across time. In the discussion on hierarchies (Chapter Two), it was noted that CAS form a series of sub or nested systems that interact with each other across the hierarchy. Because of the natural formations of hierarchies in CAS and the associated interactions across the hierarchical scales (du Plessis, 2008a, p. 79; Norberg and Cumming, 2008, p. 250), any study of CAS, and, in this case, the city, cannot be conducted without acknowledging the interactions of the systems at both the higher and lower scales (Alberti and Marzluff, 2004; Cilliers, 1998; Davoudi et al., 2012; du Plessis, 2011; Folke, 2006, 2006; Folke et al., 2004; Gunderson and Holling, 2001; Holland, 1996, 2012; Ostrom, 2007; Resilience Alliance, 2010; Walker et al., 2004).

This section will expand on how interactions at different scales affect each other by providing a brief overview of the concept of Panarchy, a concept that seeks to explain how interactions at different spatial and temporal scales affect a system and how this has been added into the framework. Examples from the case studies will then be used to illustrate how both time and spatial interaction can be identified and used within the framework.

5.3.1. Panarchy

The term *Panarchy* was introduced by Gunderson and Holling (2001) and was conceptualised to be an "integrative theory to help understand the source and role of change in systems" (Gunderson and Holling, 2002, p. 2,) as well as to explain cross-scale interactions within hierarchical systems (du Plessis, 2008a, p. 79). Panarchies are a series of nested systems that interact with each other at various spatial and temporal scales (Gunderson and Holling, 2002, p. 3). Hierarchies in CAS are not static, rather the "hierarchical levels are transitory structures maintained by the interactions of changing processes across scales" (Holling et al., 2001c, p. 72). Critical to this, as described by Holling et al. (2001b) and Folke (2006), is that larger, slower, levels of the hierarchy not only hold the system's memories, but also allow the lower, faster moving levels of the hierarchy to recover faster after a perturbation to the system. The higher levels of the system also exert controls and constraints on the lower levels. Figure 50 is a conceptual illustration of a system in Panarchal model of cross-scale interactions associated with nested systems.

The idea of panarchy is useful as it argues that transformational change within panarchies can be generated from lower levels or from higher levels, while "At the same time larger, slower levels can act to reinforce and sustain the panarchy" (Gunderson and Holling, 2002, p. 25). This can be seen in

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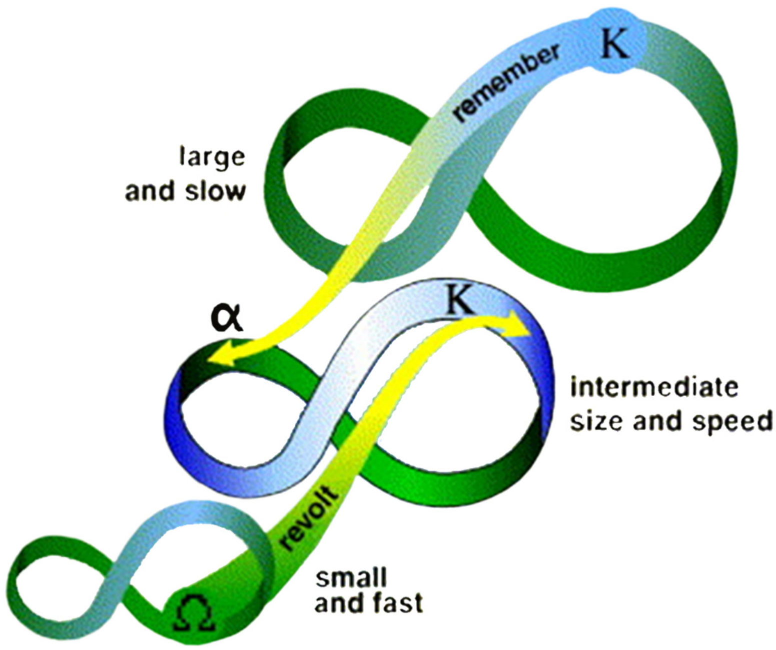

Figure 50: Gunderson and Holling's (2001) Panarchy model of nested systems that emphasises cross-scale interplay. Adapted from Folke (2006).

the '*revolt'* and '*remember'* connections, Figure 50, that occur. Revolt occurs "when fast and small events overwhelm slower and larger processes, cascading to still higher levels where these may have accumulated vulnerabilities and rigidities" (Will, 2008, p. 582). In other words, when revolt happens, lower level processes scale up past the local level and move to a higher level, causing a critical change in the system (Folke, 2006; Holling et al., 2001c). The remembered cross-scale connection uses the system's accumulated memory (i.e. institutional memory) or experience (the system's history) to create stability by drawing on the potential created by the slower higher levels (Folke, 2006; Holling et al., 2001c; Will, 2008).

Panarchy highlights the importance of mechanisms involved in cross-scale interactions. Panarchy has also been used as a tool to help identify cross-scale interactions in other studies (Alberti and Marzluff, 2004; Cumming et al., 2005; Davoudi et al., 2012; Kinzig et al., 2006; O'Farrell et al., 2008; Resilience Alliance, 2010; Walker et al., 2002) that involve complex systems.

From the above discussion, it can be argued that it is important to consider cross-scale interactions when studying any complex system. What this means for this study is, while the focal scale which is determined through the study's boundaries is indeed the most important, we must also take into consideration events at both higher and lower scales and how these impact on the focal area. This can be added to our framework and has been illustrated in Figure 51. Its application will be demonstrated as we return to the examples of Irene and Lyttelton in the following section.

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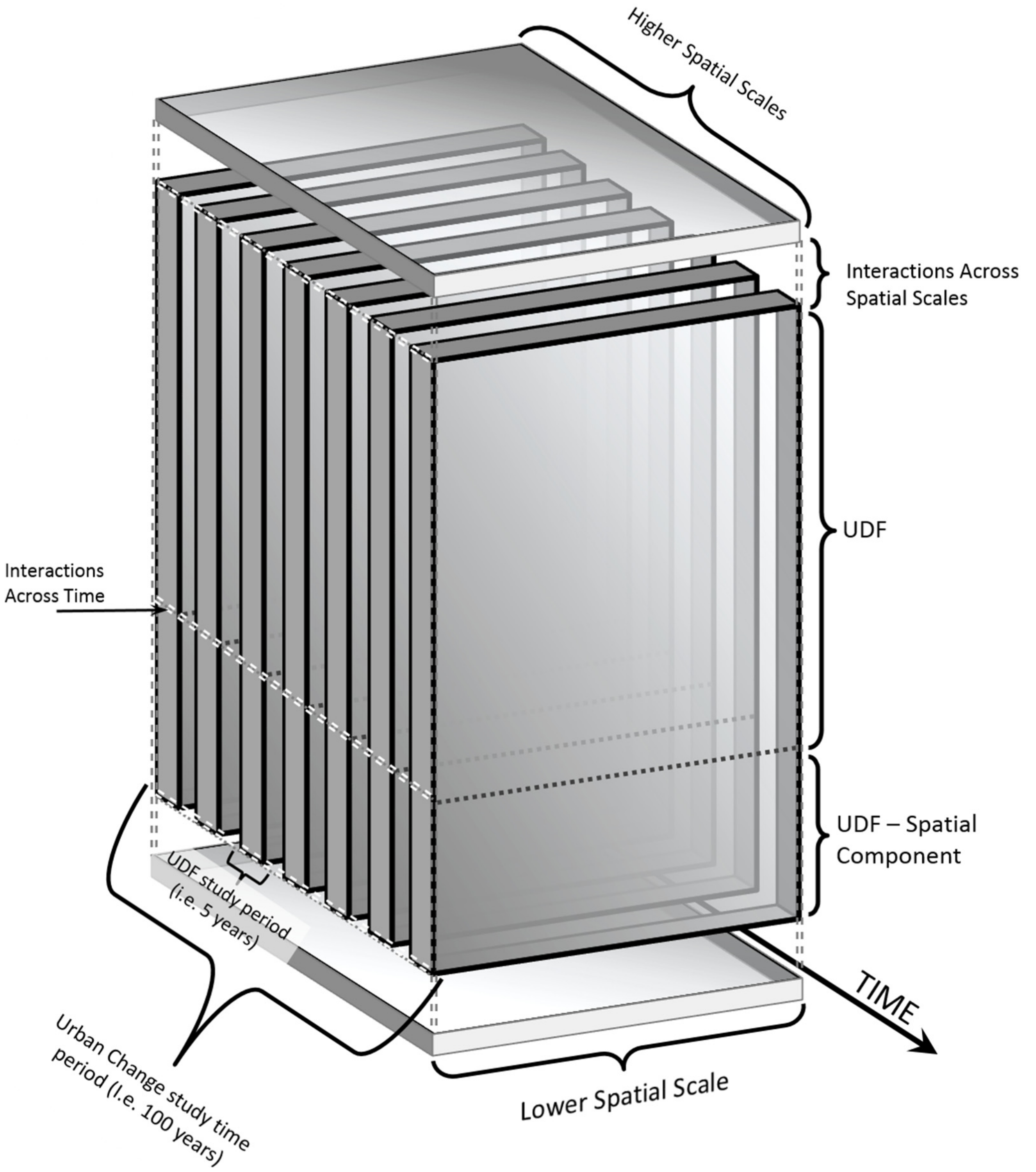

Figure 51: Addition of cross-scale interactions into the framework

5.4. Irene and Lyttelton across time and space.

As outlined in the above discussions, a system's history is important since an event in the past may have long-term consequences for the system's future. Additionally, events at higher and lower scales should also be highlighted as they, too, impact on the system's behaviour. Table 16 provides a summary of key events that happened within Irene and Lyttelton over a 110 year time period. The summary also includes some key events in higher spatial scales that had an influence on the two neighbourhoods[34].

[34] Due to the nature of the study very few lower level events were found and as a result were excluded from this example

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Table 16: Summary of events in Lyttelton, Irene, Centurion, South Africa & the world. Source (Nel, 2011)

Time Period	Events: Irene	Events: Lyttelton	Events: Centurion, South Africa and the world
Pre 1900	Irene Primary is opened	NA	Boer war
1900 - 1910	Irene Is Established; Irene Primary is reopened; Irene Homes Opens; Jan Smuts by the land next to Irene	Lyttelton Manor proclaimed	End of the Boer war
1910 – 1920	Irene golf course	Surveyor General approved the plans for the township	Union of South Africa established; First World War
1920 – 1930	Irene Library and village; electric lights		
1930 – 1940	Irene station moved north; New post office; electricity	Population of ± 30 people	During the Great Depression; the Old Pretoria-Krugersdorp road built; Dual train lines & electrification; Start of the Second World War; Rietvlei dam
1940 – 1950	Irene gets water; Irene Village Association; Irene's population is ± 800; roads are tarred;	Lyttelton X1 proclaimed; Lyttelton proclaimed Town; Village Committee created; Lyttelton gets water; New Post office; First tarred road; Laerskool Louis Leipoldt	Second World War ends; Water pipe from Vaal river to Pta; National Party elected to government;
1950 – 1960	The Oval is started; Irene X1 is proclaimed;	Lyttelton has an average growth of 11%; population 2500 people and 500 houses; 550 students at Laerskool Louis Leipoldt; Hoërskool Langenhoven opened; Lyttelton Primary opens	Apartheid Policies are enacted
1960 – 1970	streets Irene tarred; population 1000; stone walls built; police station closed	Hoërskool Lyttelton expands; Laerskool Fleur opens; Lyttelton Manor High school opens; Lyttelton Shopping centre	Economic boom; Lyttelton municipality expands and becomes Verwoerdburg: Ben Schoeman highway opened
1970 – 1980	Opening of lanes for subdivisions in Irene; Dooringkoof Primary is opened and Irene Primary loses its Afrikaans pupils	Lyttelton Manor Industrial (X4); ± 76% of the economically active population living in Lyttelton work in ISCOR, Pretoria CBD, Universities, etc.; pedestrian over Botha; extensions to Lyttelton Engineering	Oil Crisis; Geological survey is commissioned; Soweto riots and Banning of the ANC; Verwoerdburgstad new town centre

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Time Period	Events: Irene	Events: Lyttelton	Events: Centurion, South Africa and the world
1980 – 1990	Tarring of Lanes; of Village Lane built	Subdivision policy; Redevelopment of parks into retirement village; widening of Botha and Cantonments; Home affairs office	Economic decline in RSA; downscaling of ISCOR/ ARMSCOR and military employment; Town Council commissions two boreholes; Drought; Free Settlement Areas Act
1990 – 2000	Neighbourhood watch; opening of Cornwall Hill College	Widening of Lichenin; Traffic court; Urban Renewal Project	Unbanning of the ANC and 1st democratic elections; Planning Scheme for Centurion; new reservoir; Development Facilitation Act; first IDP
2000 – 2010	Gating off of Irene	Commercial development Botha Ave	City of Tshwane establishment; Global recession; Tshwane scheme

From Table 16 it is possible to identify potential frozen accidents and gateway events within the system's history. These are the key events described in Table 16. To further help identify possible frozen accidents and gateway events, the system's history was examined by using the USDF at 10 year intervals. The changes within the two neighbourhoods were primarily described through the components of the system. This is because time and data constraints limited the ability to identify, in detail, the necessary CAS properties of the system for each 10 year interval. In the case of Irene and Lyttelton, social, economic, spatial and institutional changes were considered. A summary of the changes for the two neighbourhoods in terms of the identified components can be seen in Annexure 7, which has been further summarised in Figure 52[35].

To understand if an event warranted being called a frozen accident or a gateway event, the circumstances that created each event, as well as the long term effects of the event on the system, were further explored. The first step was to differentiate between small, medium and large events, the large events being considered as gateway events as they had a large, long-term impact on the two areas. For example, in Figure 52 for both Irene and Lyttelton, the creation of a train station (pre-1900)

[35] This is only a clip of the full image which can be seen in Annexure 8.

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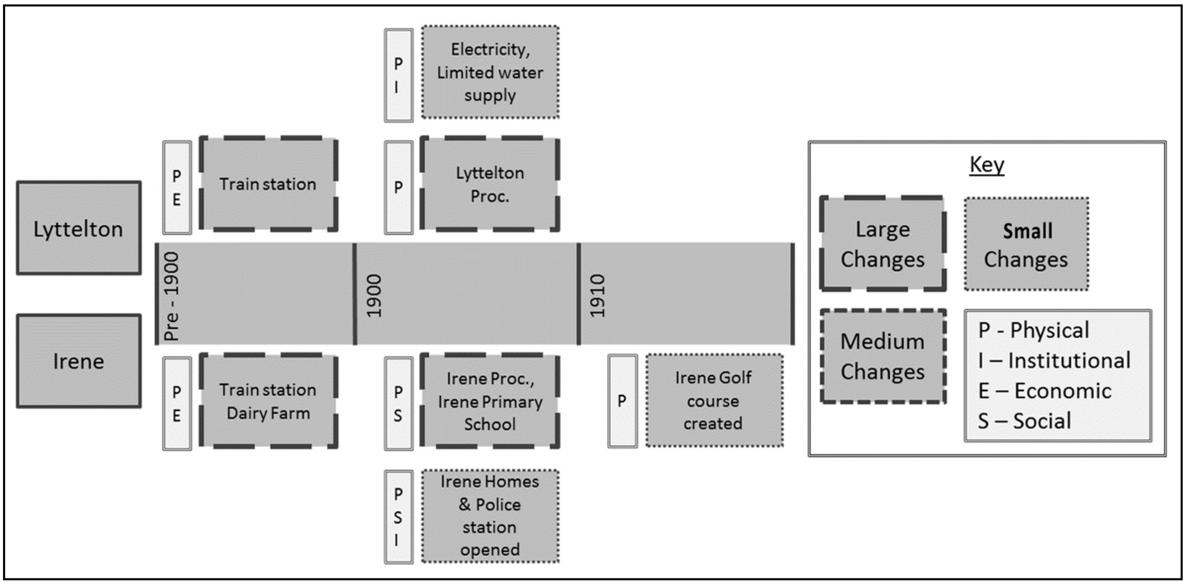

Figure 52: A breakdown of the events, characteristics and magnitude of changes for Lyttelton and Irene. Adapted from Landman and Nel (2012, p 5)

and proclamation (1900s) of the two neighbourhoods radically changed the system in each area and set them onto a particular trajectory. The small and medium changes were seen as frozen accidents as they had only a minor impact on the long-term behaviour of the system and the collection of small changes became regularities within each neighbourhood.

Of the cross-scale interactions taken into account, the pattern for both Irene and Lyttelton was that they had little or no discernible impact on the higher tier systems (national and global systems). However, both had an impact on the intermediate level (city). For both neighbourhoods, at various points in time, this was in the form of either creating or allowing growth and change (i.e. rapid growth of Lyttelton in the 1950s allowed for the creation of Centurion Town) or by resisting or preventing growth or change within their areas (i.e. Irene's residents resisting the development of a new major road next to the neighbourhood preventing expansion of the city). In both cases this resulted in knock-on effects that impacted the larger city.

By far the larger and perhaps the most easily identified interactions and impacts were those of the higher level system's impact on the lower level system. These can be seen in, for example, the impact of national economic decline (the scaling down of ARMSCOR), municipal sub-division policy (allowing for renewal within Lyttelton) or opening of post offices and schools within each area (facilitating growth around the facilities)

5.5. Conclusion

In this chapter the addition of time was highlighted as an important aspect when studying any complex system. Frozen accidents and gateway events are events or changes that have an impact on the system's long-term behaviour. The collection of frozen accidents and gateway events in a system's past can lead the system onto a particular trajectory called path dependency.

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Simultaneously to taking a system's history into account, any complex system cannot be reduced to a two dimensional construct. Instead, they can be seen as a three dimensional layering of sub-systems that, together, create the larger system. The various levels of any system change at different rates. The higher levels tend to change at a slower rate than those at the lower levels (Folke, 2006). Additionally, the various levels interact with each other. In doing so, they provide another dimension to the change that occurs in a CAS. As a result, cross-spatial scale interactions were included in the framework.

A broad overview of system change over time, while considering its relationship to higher and lower scales, can reveal patterns of past disturbances and responses, and reveal cumulative impacts for a set of changes (Resilience Alliance, 2010).

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Chaper 6: The nature of change

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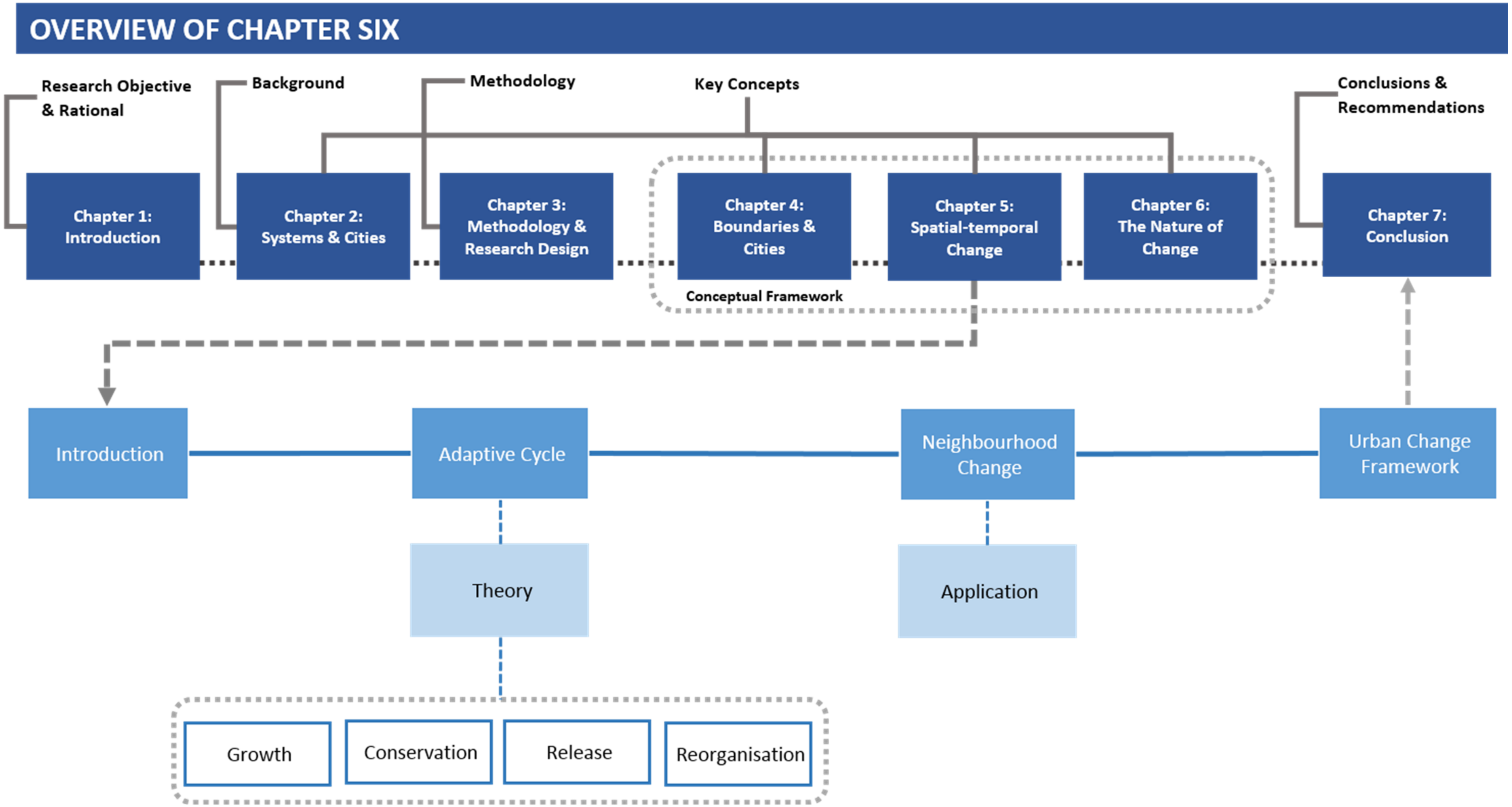

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6.1. Introduction

In the previous sections, the need for boundaries was identified as being of great importance when studying CAS, following which a framework for describing the urban system from a CAS perspective was proposed. The framework was then expanded to include cross-temporal and scale interactions when seeking to identify change in a system. The latter is vital as it is a prerequisite for the description of change. Changes identified in chapter five will 'plug' directly into the discussion of this chapter, as has been outlined in Figure 53.

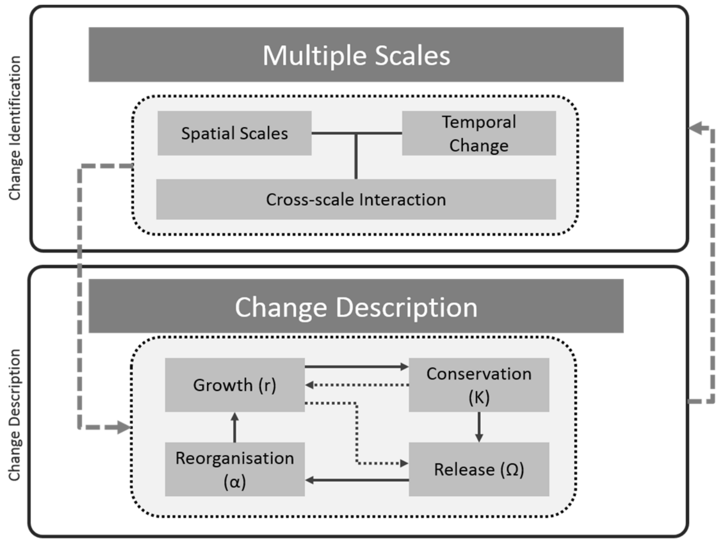

Figure 53: Changes identified are described according to the nature of the change.

This chapter will explore the nature of change. The metaphor of the adaptive cycle, taken from social-ecological systems theory for use in understanding the resilience of a system as it transitions between four distinct phases (Peter and Swilling, 2014) will be used. After discussing the adaptive cycle, the focus will return to the examples of Lyttelton and Irene and how the concept of the adaptive cycle has been applied to both neighbourhoods.

6.2. The Adaptive Cycle

In resilience theory, the adaptive cycle is used to conceptualise the transitions of a social-ecological system between regimes (Peter and Swilling, 2014, p. 1602). The adaptive cycle was first developed by Holling (1986)[36] to be a general framework to describe the changes in SES, and by extension CAS, as they move through four distinct phases (Holling and Gunderson, 2001). The various phases in the adaptive cycle are primarily described by considering a system's *potential,* i.e. the systems potential for change and accumulation of resources or capital in the system (Holling and Gunderson, 2001; Will, 2008), and *connectedness*, which is best described by Gunderson and Holling (2002, p. 6) below.

> "Low connectedness is associated diffused elements loosely connected to each other whose behaviour is dominated by outward relations and affected by outside variability. High connectedness is associated with aggregated elements whose behaviour is dominated by inward relations among elements of the aggregated, relations that control or mediate the influence of eternal variability"

[36] This was developed further by Gunderson and Holling (2001) to include cross-scale interactions of nested systems called Panarchy (see chapter 5)

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In other words, connectedness refers to how connected the processes and controlling (internal) variables are, and whether or not their behaviour is dominated but internal or external forces (Holling and Gunderson, 2001; Will, 2008). The various phases of the adaptive cycle are: *Growth*; *Conservation*; *Release* and *Reorganisation*. They are described in further detail below and summarised in Table 17. Figure 54 illustrates the adaptive cycle with the movement of the system from growth to conservation to release and, finally, to reorganisation.

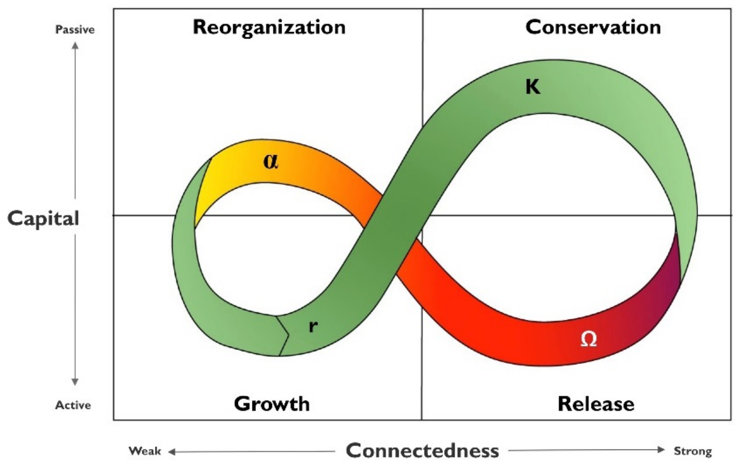

Figure 54: The Adaptive Cycle. Image source Noah Raford (2013), adapted from Gunderson and Holling (2001)

Table 17: Summary of the Characteristics of the Phases of the Adaptive Cycle

Phase of the Adaptive Cycle	Characteristics of Each Phase
Growth (r)	• Rapid growth • Weakly interconnected internal agents • Poor internal control • Contest, competition • Connectedness increases • Diversity increases • System more vulnerable to surprise
Conservation (k)	• Accumulation of resources • Connections increase and are strengthened • Slowing growth rate as connections increase • Increased dependence on existing structures • Increase in stability but over a decreasing range of conditions • Slow and incremental change
Release (Ω)	• Release of resources, i.e. Material and energy gathered in conservation phase (K) • The release of resources happens abruptly • Creative destruction
Reorganisation (α)	• High potential, • High resilience • Low connectedness, poor internal regulation • Uncertainty (areas in decay ripe for renewal) • Enables experiments

The first phase of the adaptive cycle is that of the growth phase and is denoted by (**r**). This phase occurs early in the cycle and is characterised by a period of rapid growth, disorganisation and an accumulation of resources. Successful agents (often innovators or entrepreneurs in economic systems) utilise opportunities that are created after a disturbance and make use of this time to exploit new niches (Holling et al., 2001b; O'Farrell et al.,

In the urban system the growth (r) phase can be seen as when people move into a newly established area (Alberti and Marzluff, 2004, p 249).

2008). There is an increasing amount of diversity as the system grows; but the system is more vulnerable and far more easily influenced by external variability. This is due to the system components being weakly interconnected with little or no internal regulations (Holling and Gunderson, 2001). The agents (individuals) that function best in this phase are those best "adapted to dealing with the stress and opportunities of a variable environment – the risk takers, the pioneers, the opportunists" (Gunderson and Holling, 2001, p 43). They typically operate at a local scale and over short time periods.

As the system grows and accumulates more resources, it slowly and incrementally begins to move into the second phase of the adaptive cycle, the conservation (K) phase[37]. The "progression from the phase r to K (conservation) is when patterns reinforce and the system becomes more rigid" (Alberti and Marzluff, 2004, p. 249). Part of this process is due to the system's elements that tend to do well now changing from those not as sensitive to external changes and uncertain circumstances (entrepreneurs) to those that reduce the impact of external variability through mutually reinforcing relationships (bureaucracy) (Gunderson and Holling, 2002; Holling and Gunderson, 2001). This is, in part, due to there being more competition between the system elements as available resources become divided and the growth of the system slows down (Holling and Gunderson, 2001). The fact that the system elements are less vulnerable to external variability means that the system becomes more stable. However, stability comes at a price as the system is able to deal with a decreasing range of situations. As a result, the system loses much of its resilience (Holling and Gunderson, 2001). The shift from the conservation (k) phase to the release (Ω) phase can take place at any time, as the system is now more vulnerable to external shocks (Alberti and Marzluff, 2004).

In the urban environment "the conservation phase (K) [can be seen] when urban population growth leads to unchecked growth and urban sprawl" (Alberti and Marzluff, 2004, p 249).

When a system transitions into the release (Ω) phase (also called creative destruction), this is usually rather sudden and takes place when a disturbance pushes the system past a particular point or threshold and breaks its resilience (Alberti and Marzluff, 2004; Cumming et al., 2005; Gunderson and Holling, 2002; Holling and Gunderson, 2001; Walker et al., 2004). During this transition "strong destabilizing positive feedbacks develop between the revolting elements (the insect defoliator, the aroused stock-holder) and the established aggregates (the trees in the mature forest, the bureaus of the firm)" (Holling and Gunderson, 2001, p. 45). This results in the release of resources accumulated during the conservation phase, as the strict regulations and interconnectedness of the system are now broken. The release of resources is only temporary and the potential in the system decreases suddenly. This continues until the disturbance has dissipated (Holling and Gunderson, 2001, p. 45).

The final phase of the adaptive cycle is the reorganisation (α) phase. Here the shift from Ω to α, which happens quickly, is characterised by high potential, weak connections and internal controls. This,

[37] The movement from the growth (r) to the conservation (K) phases is often referred to as the 'fore' or 'front' loop' of the adaptive cycle, while the release (Ω) and reorganization (α) phases are called the 'back loop'(Folke, 2006; Resilience Alliance, 2010; Walker et al., 2004).

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however, allows for innovation and creativity within the system (Holling and Gunderson, 2001, p. 45). Small, random, events have the ability to shape the system's long term history[38] and set it onto a path dependency (Gunderson and Holling, 2001). Because of the increase in uncertainty and weak connectedness, the system experiences periods of chaotic behaviour followed by brief periods of stability. This process encourages the development and maintenance of diversity within the system. The increased diversity allows the system to respond quickly to unexpected external changes (Holling and Gunderson, 2001).

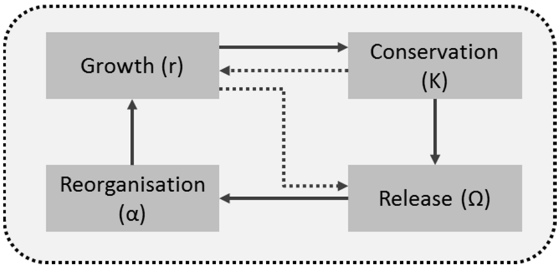

Figure 55: Alternative Paths of the Adaptive Cycle. Derived from Walker et al. (2004)

As shown in Figure 54 the metaphor of the adaptive cycle forms the infinity symbol (∞) which represents the continual iteration of the adaptive cycle, i.e. that there is no end or beginning. Additionally, "the idea of adaptive cycles should not be taken as necessary sequences of clearly identifiable phases in a mechanistic process" (Lang, 2012, p. 288). Instead, "adaptive cycles and their outcomes should be considered as tendencies rather than inevitabilities" (Davoudi et al., 2012, p. 305). This point is further argued by Walker et al. (2004, p. 2) who claim that the adaptive cycle has been "based on observed system changes, and does not imply fixed, regular cycling. Systems can move back from K toward r, or from r directly into Ω, or back from α to Ω". What this means is that a system need not follow the typical sequence of the adaptive cycle, as seen in Figure 54, but that a system can follow an alternative sequence between the phases. There is a chance that the system may 'skip' a phase or even go back to one from which it has just come. This has been illustrated in Figure 55 where the alternative paths that the system may take along the adaptive cycle are shown. The dark line in Figure 55 represents the sequence described by Holling and Gunderson (2001), and the lighter, dashed lines, show the alternative paths described by Walker et al. (2004, p. 2). Lastly, adaptive cycles occur and interact at various scales. These cross-scale interactions of adaptive cycles form into panarchies[39] (Folke, 2006; Gunderson and Holling, 2001; Kinzig et al., 2006; Walker et al., 2004). Holling et al. (2001a, p. 400). Table 18 provides some examples of how the phases of adaptive cycles may appear in different types of systems.

Table 18: Examples of the Four Phases of the Adaptive Cycle in Different Systems. Adapted from Holling et al. (2001, p 400)

System Type	Phase of the Adaptive Cycle			
	Growth (r)	Conservation (k)	Release (Ω)	Reorganisation (α)
Ecosystem	Exploration	Conservation	Release	Reorganise
Economics	Market, entrepreneur	Monopoly, hierarchy	Creative destruction	Invention
Organisation	Adhocracies	Bureaucracy reutilization	Catalysts, heretics	Visionary
Institutions	Markets	Hierarchies	Sects	Isolates
Individuals	Sensation	Thinking	Intuition	Feelings

38 In this phase frozen accidents and gateway events have a high chance of happening. Additionally this is also the phase that is most likely to shift the system into a different stability regime (Gunderson and Holling, 2001)
39 Panarchy has been discussed in Chapter Five.

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While the examples given in Table 18 provide insight into the changes of different systems, many of which form part of the urban system, the question still remains if the adaptive cycle can be applied to the urban system? If the adaptive cycle can be applied, what would the typical phase look like for the urban system? The section to follow will attempt to apply the adaptive cycle to the case studies of Irene and Lyttelton in an attempt to describe the changes of these two neighbourhoods according to the adaptive cycle.

6.3. Neighbourhood change

In an attempt to describe urban changes according to the adaptive cycle, our attention is brought back to Irene and Lyttelton. To apply the adaptive cycle to these two neighbourhoods, the histories and changes identified in Chapter Five will be taken further and looked at through the lens of the adaptive cycle. This has been summarised in Table 19 and graphically illustrated in Figure 56.

Table 19 was compiled by comparing the changes that have taken place over the history of the two neighbourhoods, as described in Chapter Five, and then considering the characteristics of each phase of the adaptive cycle[40]. The size of the changes (small, medium and larger changes) identified in Chapter Five were used as a means of weighting the changes and to help identify if that particular event 'pushed' or 'pulled' the system to another phase in the adaptive cycle. Additionally, the event itself and the circumstances around it provided further context and insight to the nature of the change, and further helped in using the adaptive cycle to understand the changes in these neighbourhoods.

Table 19: Irene and Lyttelton's History When Compared to the Phase of the Adaptive Cycle. Adapted from Landman and Nel (2012)

Phase	Irene	Lyttelton
Growth (r)	1900s – 1960 Initial rapid growth of the neighbourhood. From the late 1950's there is a slowing down of this and an increasing amount of internal regulation and internal connectedness.	1900s - 1940s Very slow growth due to limited resources, water. 1940s – 1970s Rapid growth of the neighbourhood due to having access to water as well as ISCOR and ARMSCOR opening close to the area, provided many job opportunities (post WWII). This was further supplemented with the development of the Lyttelton shopping centre in the 1960s.
Conservation (K)	1960s – Present From the 1960 to the current day has been characterised by continuous closing off and withdrawal of the community with most changes accentuating and increasing	In the late 1970s this growth started to slow down due to, among other things, the aging population and sinkholes. It would seem that the neighbourhood was going into this phase but for the most part

[40] A similar process was done by Walker et al. (2002) in their proposed framework for analysing social-ecological resilience. Whereby they looked at the history of the SES that was being studied and plotted the historical events and changes against the adaptive cycle

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Phase	Irene	Lyttelton
	the isolated nature of the neighbourhood. Irene remains here due to its strong internal controls and limitations of allowed changes. However it is able to manage the pressures due to the many available resources.	it skipped this phase at this time and moved to the Ω - Release phase.
Release (Ω)	Not happened yet	1980s This phase did not last very long, nor should it. This phase was initiated by the fact that, due to the aging population of Lyttelton, retirement villages were opened. This, as well as a flood of subdivision applications, meant that there was land available for young families to move in to be close to the schools. This led to the development of an urban renewal policy for the area. This urban renewal helped push the neighbourhood into the next phase of the adaptive cycle .
Reorganisation (α)	Not happened yet	Late 1980s- 1990s With the changes driven from the urban renewal policy as well as the closing of ARMSCOR and ISCOR the area also had many changes in land use coupled with the opening of many home based businesses.
Growth (r)	Not happened yet	1990s The α phase, and the renewed energy that came from it created competition between developers and residents regarding residential land uses with a variety of non-residential land uses being developed, especially along main roads. The ethnic composition of neighbourhood and schools changed, due to national political changes.
Conservation (K)	Not happened yet	2000s As the area moved into the new millennium the residential function still remains due to stabilising influence of schools, but the character of the neighbourhood has changed from integrated neighbourhood to fragmented one with increasing non-residential edges.

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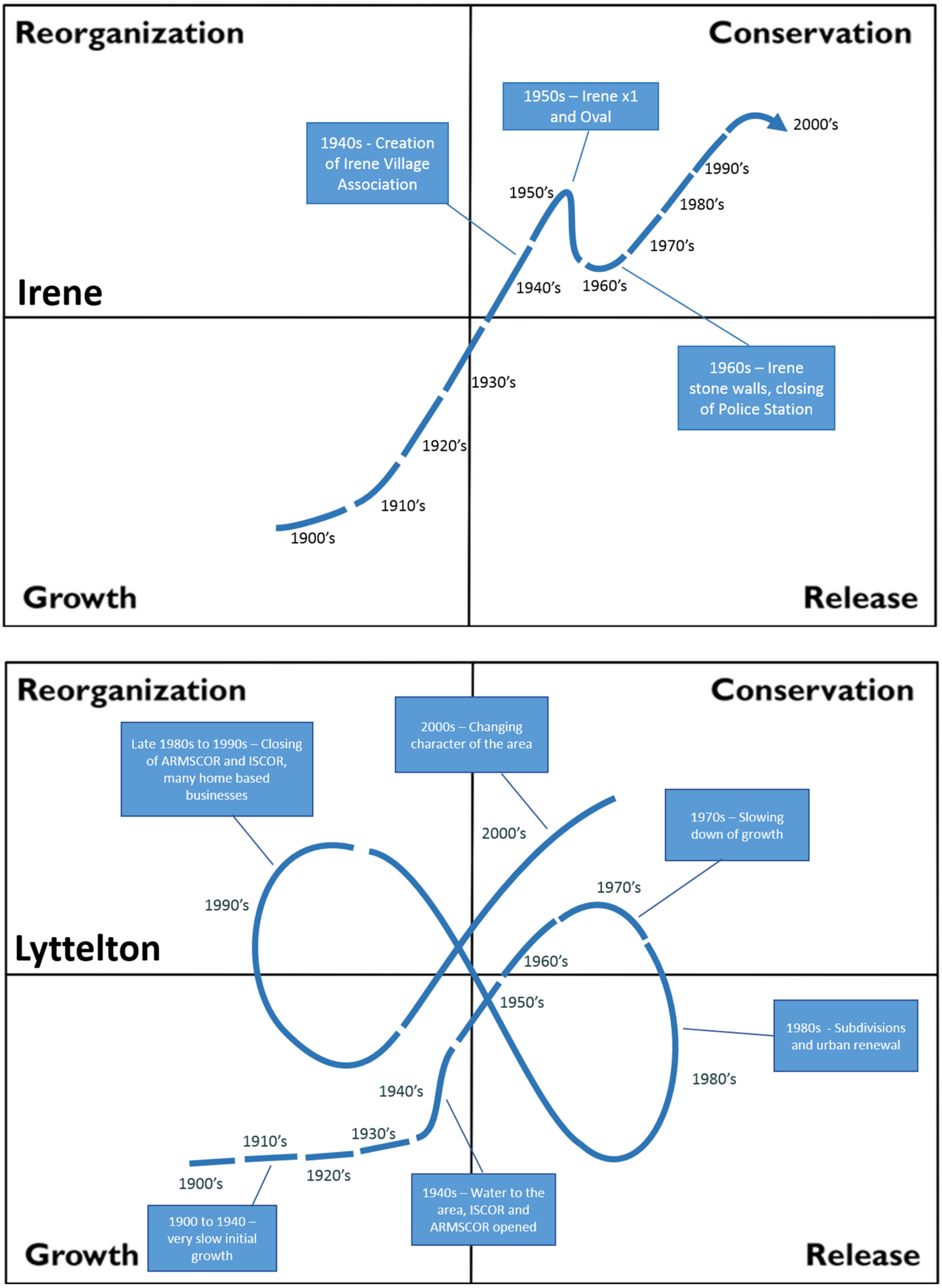

Figure 56: The movement of Irene (top) and Lyttelton (bottom) through the adaptive cycle over time. Each dashed line represents a ten year period. Adapted from Nel and Landman (2012)

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Table 19, as illustrated in Figure 56, shows how the adaptive cycle can be used to describe the changes of the two neighbourhoods. From the descriptions provide in the Table it is unmistakeable that the changes within Irene and Lyttelton are very different to each other. Where Irene grew rapidly in the first half century, Lyttelton's initial growth was very slow. This was largely due to the fact that Irene had access to basic services, such as water (and later electricity), and was close to a dairy farm (where residents could purchase milk and butter). This led to the creation of other services such as a school and a post office, which further increased the growth of the township. This, however, changed when Lyttelton received piped water from Rand Water[41] and the post-world war two government located two large corporations (ARMSCOR and ISCOR) in close proximity. Both neighbourhoods continued to grow until the 1960's. This changed when Irene began to move into a conservation phase. This was largely due to the creation of the Irene Village Association, which was formed to protect the property owner's interests, and relocation of the local police station, which resulted in Irene reacting to the threat of crime by building large stone walls around the neighbourhood, an example of which is provided in Figure 58.

Figure 58: Example of the Irene Stone Walls

Irene began to move to the release phase when the lanes were widened, allowing for extra access to the properties and encouraging subdivision of land. This would have allowed Irene to move into the release phase, but the properties within Irene have a restrictive title condition which states that, for any changes to take place on the properties within Irene, residents must first get the permission of the farm's owner. This, coupled with the conservative nature of the residents limited the potential created by the opening up of the lanes in Irene.

Figure 57: Gating off of Irene with controlled access into the neighbourhood (top) and blocked off streets (bottom).

The conservative nature of the residents of Irene was further entrenched after a series of break-ins and a murder. The neighbourhood reacted to this by further isolating itself by closing off access to the neighbourhood, except for a few access-controlled points. Examples of the closing off the neighbourhood have been showing in Figure 57. Irene has largely remained in the conservation phase

[41] Rand Water is a water services provider in South Africa.

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due to the political and financial resources available to it from the residents. The future movement of Irene through the adaptive cycle is still to be seen.

In contrast to Irene, Lyttelton has moved quite rapidly through the adaptive cycle. This was a result of several factors. As mentioned above Lyttelton's initial growth was very slow when compared to Irene. This changed when the neighbourhood was given access to services and new work opportunities opened in close proximity to Lyttelton. The neighbourhood began to move into a conservation phase due the aging population and the discovery of Dolomite[42] in the area. Lyttelton did not spend much time in the conservation phase, as it moved into the release phase after about two decades. It was able to move into the release phase by releasing the available resources (in the form of land) in the area. It did this by encouraging the subdivision of land, after a geological survey, and by constructing two retirement villages, thereby releasing more land into the area and allowing new, younger families to move into the area.

In addition to the release of land and the movement of young families into the neighbourhood, the change in political regime (the end of Apartheid) and closure of ISCOR and ARMSCOR also had an impact on Lyttelton. The change in the political regime allowed people of colour to stay in the area. This brought a new diverse population into the area, bringing with them new ideas and ways of doing things. With the closure of ISCOR and ARMSCOR, many of the employees were given severance packages. As a result, many of the former employees began home based businesses within Lyttelton. Another factor that played a role was the urban renewal policy the Municipality began to implement at the time. The combination of these changes restructured Lyttelton and, in essence, allowed for it to reinvent itself, but without changing its primary function, that of a residential area.

Table 19 and the illustration in Figure 56 show how the adaptive cycle can be used to describe and characterise the changes that the two neighbourhoods have undergone. Based on the findings from Irene and Lyttelton, it is possible to add a preliminary, additional example of the phase of the adaptive cycle to those already provided by Holling et al. (2001, p 400), Table 18. This is shown in Table 20 and presents possible examples for the phase of the adaptive cycle applicable to neighbourhoods.

Table 20: The Four Phases of the Adaptive Cycle in the Urban Neighbourhood. Derived from examples of Irene and Lyttelton. Adapted from Holling et al., (2001, p 400)

System Type	Phase of the Adaptive Cycle			
	Growth (r)	Conservation (k)	Release (Ω)	Reorganisation (α)
Urban system (Neighbourhood level)	Establishment and construction of buildings and services. Movement in of new population	Aging of population (resistant to change and conservative) Aging infrastructure	Subdivision/ consolidation of land. Redevelopment of land	Change in population demographics (i.e. Influx of younger population) Changes in land use

[42] Dolomite is a rock formed from calcium magnesium carbonate and is typically associated with the formation of sinkholes, making it difficult and costly to build on (Wagener and Day, 1986).

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System Type	Phase of the Adaptive Cycle			
		Creation of community forums. Closing off of an area as a reaction to crime		

Looking at the histories of the two neighbourhoods and how they fit into the adaptive cycle, as seen in Table 19 and illustrated in Figure 56, it can be argued that the adaptive cycle can be used to describe changes to the urban system, at least on a neighbourhood level. Further questions to be asked are if the adaptive cycle can be used on other neighbourhoods and on different scales.

6.4. Urban Change Framework

The aim of the Urban Change Framework (UCF) described above, and illustrated in Figure 59, is to be able to describe the urban system at a given point in time, and then to use this description to describe the change of that system over time. In order to achieve this goal, several steps were followed. These steps can be grouped into three main components, namely: (1) system description, (2) change identification and (3) change description.

The first component, system description, is made up of two parts. The first of these is boundary creation. Boundaries are placed on the study/research (to make it manageable) and also on the system being studied. The second part consists of the description of the system being studied at a given point in time. By describing the system at various points in time it allows for the identification of changes within the system across time.

The changes identified are not only on the system/focal scale but also include the scales above and below the system of interest. This is done because CAS cannot be looked at in isolation. This was shown in the case studies, where events on scales above had an impact on the focal systems.

The last part of the framework (change description) described in this chapter, links to the rest of the framework by making use of the changes identified in the previous component, i.e. change identification and applying the identified changes to the adaptive cycle as a means of describing the changes based on the characteristics of the various phases of the adaptive cycle. The explorative framework outlined in this study aim is to help and enable researches and practitioners within the planning fraternity to conduct longitudinal studies into urban change, with the specific goal of applying the findings to a resilience framework.

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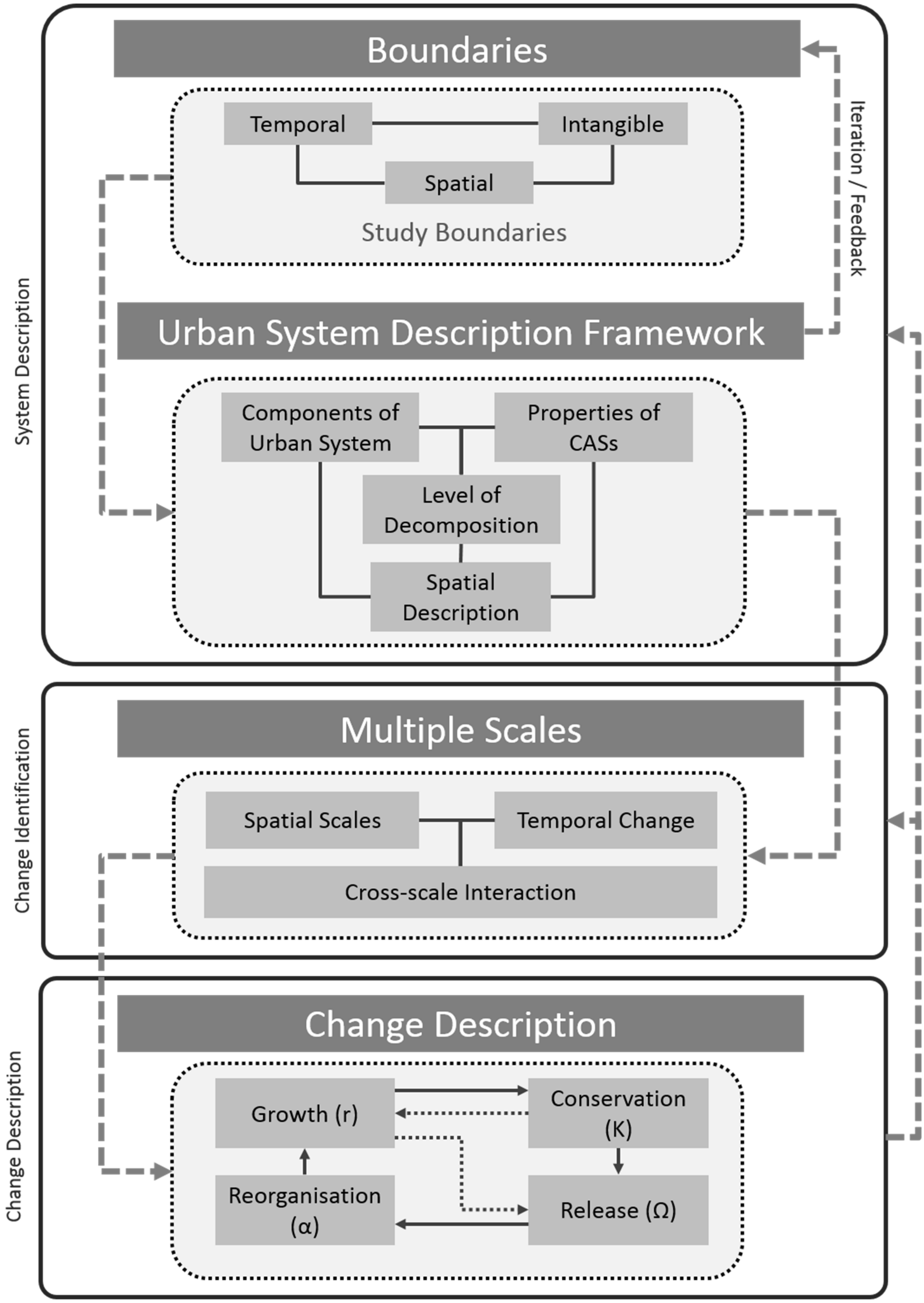

Figure 59: The Completed Urban Change Framework

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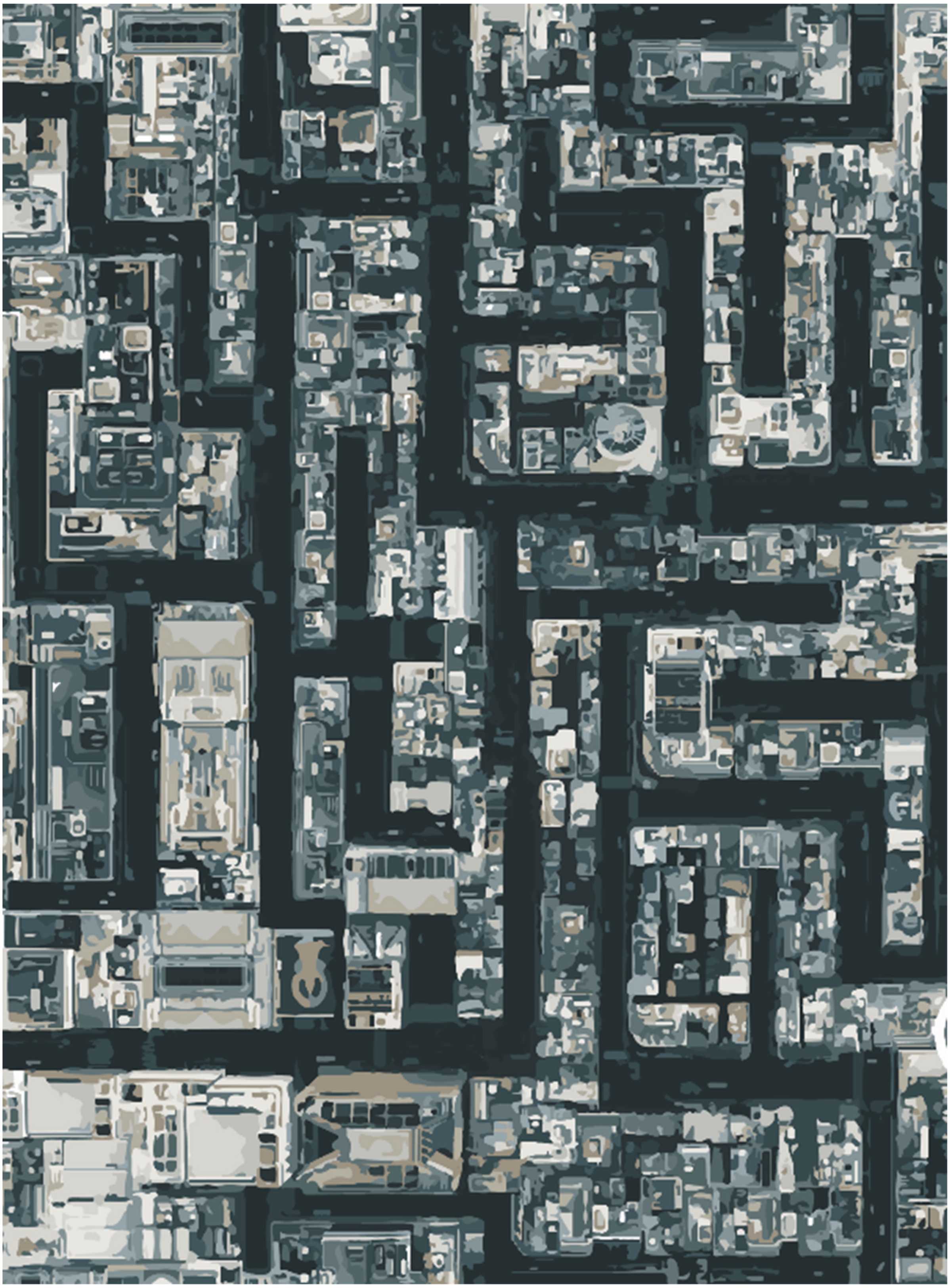
Chaper 7: Conclusion: Getting from here to there and beyond



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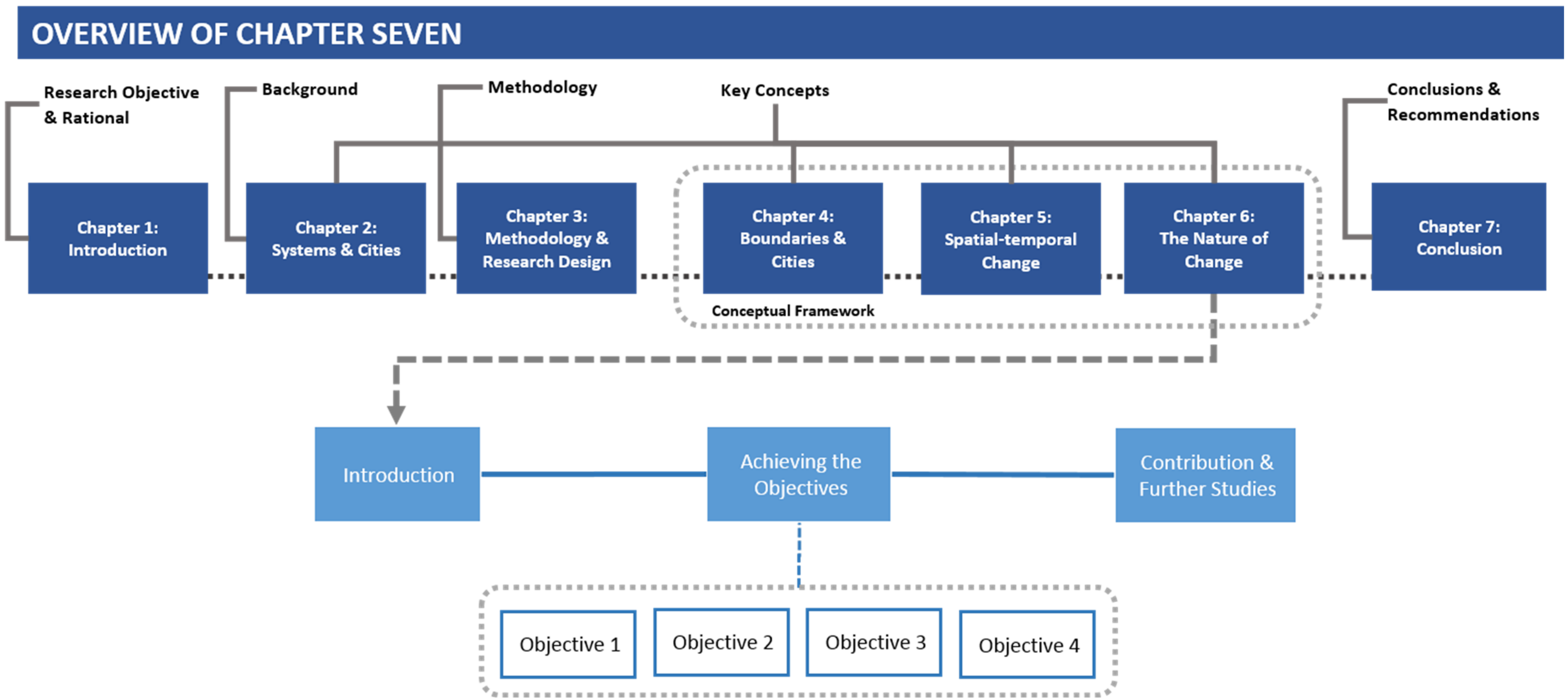

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7.1. Introduction

With the present challenges cities are facing of rapid urbanisation, strained and aging infrastructure, social unrest and the increasing impacts and concerns of climate change, the pressure on urban planners and cities to provide appropriate solutions has never been greater. At the same time, the need for cities to adapt and prepare for the unknown has also increased. Urban resilience presents a possible solution to manage these challenges. However, there is very little consensus on what exactly resilience is (Davoudi et al., 2012, p. 299). Despite the lack of clarity, a multitude of resilience assessment frameworks and methodologies have been created, chief among them being the Resilience Alliance's (2010) workbook for assessing the resilience of SES.

This study arose from the challenges faced while attempting to assess the resilience of two neighbourhoods in Tshwane, namely Irene and Lyttelton, by applying the Resilience Alliance's (2010) resilience assessment workbook. The challenges identified can be summarised as: the workbook does not provide adequate guidance (1) on how to set boundaries on a system, (2) describe a system and (3) how to identify and describe change within a system. These challenges were further compounded when attempting to apply the framework, which is primarily focused on ecosystems, to the urban system (Nel et al., 2013).

This chapter reviews the objectives of the study and asks whether they been met. It then outlines the findings, contributions and implications of the study. This chapter, as well as the dissertation, concludes by providing suggestions for future research.

7.2. Achieving the objectives

This study set out to achieve four main objectives in order to overcome the challenges identified above. The objectives of this study are: (1) to identify a theoretical basis that can describe the behaviour, structure and changes of cities; (2) to develop a framework for describing an urban system; (3) translate resilience theory constructs for mapping change into the urban context and (4) to illustrate the application of the concepts to the urban environment.

This section will present each of the objectives of the study and will then discuss how each of the objectives have or have not been achieved.

7.2.1. Objective 1: Identify a theoretical basis to describe the behaviour, structure and change of cities.

The first objective of this study was to identify a theoretical basis that can describe the behaviour, structure and changes of cities. In doing so this objective provides the theoretical point of departure that will serve as the basis for the study and from which the other objectives build on.

As this study seeks to supplement existing resilience frameworks, like the one created by the Resilience Alliance (2010), it will have to ensure that the input into these frameworks is compatible in

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terms of its theoretical underpinnings as well as its practical applications. In order for this to happen a review of the literature of resilience theory was done, see Chapter 1 and Chapter 2 (section 2.6.10.), where by it was shown that resilience is a property of a complex adaptive system (CAS) (Folke, 2006; Holland, 2012; Holling, 1986; Page, 2011) and that in order to study the resilience of social-ecological systems a complex adaptive systems' is the most appropriate (Elmqvist et al., 2004; Gunderson and Holling, 2001; Norberg and Cumming, 2008; Peter and Swilling, 2014).

Complexity theory has been argued to be the most appropriate approach for studying the resilience of social-ecological systems. As one of the underlying assumptions of this study, and supported by Davoudi et al (2012), Evans (2011), du Plessis (2009, 2008a) and Roggema (2012), is that cities are not only complex adaptive systems but are also social-ecological systems a complexity theory based approach is deemed as the most appropriate for this study.

Furthermore, a complexity theory approach emphasis understanding the processes that create the behaviour of CAS as well as understanding the adaptive (changing) nature of CAS.

The final reason for using a complexity theory approach for this study is that all CAS exhibit the same or similar properties (Beinhocker, 2006; Brownlee, 2007; Gell-Mann, 1994a; Health Foundation, 2012; Holland, 1996, 1992b; Innes and Booher, 2010; Lucas, 2006; Page, 2011), although these properties may manifest in different ways. Chapter 2, Section 2.7., illustrated how the various properties of CAS can be seen within the city. Based on the fact that CAS exhibit the same or similar properties, it was assumed that various CAS could be compared to each other by using their properties as a 'normalisation' or 'proxy' for comparison.

7.2.2. Objective 2: To develop a framework for describing an urban system.

This objective is a response to the fact that the Resilience Alliance's (2010) workbook argues that the first step in doing a resilience assessment is to first describe the focal system. The Resilience Alliance (2010) suggest that in order to describe the system one must first set soft boundaries on the system after which the main components of the system should be identified. This proves to be somewhat problematic as the Resilience Alliance (2010) does not give clear guidance on how this should be done. This problem is further compounded when the Resilience Alliance's (2010) framework is applied to the urban environment which, unlike environmental sciences, does not have any clear methods or frameworks in place to assist in this matter. For this reason the second objective of the study was to develop that can be used to describe the system that is being studied. As shown in Figure 60 this framework will have to give guidance on: (1)

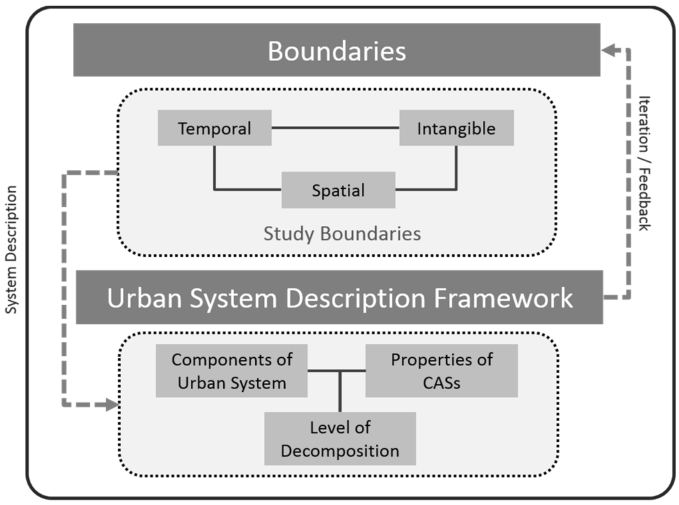

Figure 60: Urban Description component. Made up of setting

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how to set boundaries on a focal system; and (2) how to describe the urban system as well as its behaviour and structure. In order to achieve this objective, it was split into two parts. The first considered aspects of setting boundaries on the focal system. While the second focused on describing the system of interest. Each of these will be discussed in turn.

In order to determine how to set boundaries on a system a literature review was conducted to determine what boundaries were exactly, if they were indeed necessary, the various types of boundaries and how to place these boundaries on a system. The discussion of the literature on boundaries in Chapter 4, Section 2 showed that although there is no general consensus on how to set boundaries on a system, there is an agreement that boundaries are needed in order to study CAS. Additionally, the discussion showed that there are three main types of boundaries that can be placed. These being spatial boundaries (providing a spatial demarcation to the study), temporal boundaries (set the time period that the system will be studied in) and finally intangible boundaries (includes non-physical human and or non-human aspect). The application of each of these types of boundaries was illustrated by using the examples of Irene and Lyttelton.

The second part in achieving this objective was to provide a method or framework that can be used to describe the urban system. The Urban System Description Framework (USDF) was developed specifically to describe the urban system. The USDF uses three main parts to describe a system. The first part is the ability of a system to be partially decomposed onto smaller, more manageable, subsystems. The decomposition of a system should not be confused with reductionism as one must still keep in mind that the subsystem is still part of a larger system and cannot be seen in total isolation (Ostrom, 2007).

The second part of the USDF (discussed in Chapter 4) uses the fact that systems can be partially decomposed and by using this a system can 'ordered' into various subsystems. These subsystems can be sorted or defined in various ways. This ability allows for the natural creation of the various components that the city is usually studied in, i.e. social, economic, institutional, etc. By using the various, existing, components of the city makes sorting or managing the study of the urban system easier and more manageable (Reif, 1973, p. 26).

The final part of the USDF uses the properties of CAS[43], which are common denominators in all CAS, as a means to identify and describe the various components of the urban system. The components of the system and the properties of CAS are then placed into a matrix which can be used to then identify the common characteristics of the system from various perspectives and in doing so provide a description of the system for the selected time period.

The USDF was then taken further by including a spatial component to the description of the system. This was done in order to provide a more complete picture of the system as some aspects of the system can only be properly understood when described spatially. In order to describe the system

[43] The various properties of CAS are discussed in detail in Chapter 2 Section 2.6.

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spatially the properties of CAS where translated into the spatial dimension and examples where provided on how each of the properties can be seen spatially.

By being able to set boundaries and by combining the spatial and non-spatial description of the system a more complete picture of that system, at a particular point in time, can be created. In doing so we are now able to comply with the Resilience Alliance's (2010) framework which requires that (1) boundaries be placed and (2) that it is necessary to provide a description of the focal system before any assessment of the resilience of the system can be done. Furthermore, by achieving this objective this study illustrated how boundaries and a description of the system can be done in the urban context.

7.2.3. Objective 3: Translate resilience constructs for mapping change into the urban context.

Objective 2 reasoned to the first two challenges that were identified, namely how to set boundaries and describe a complex adaptive urban system. Without achieving the Objective 2 this study would not be able to respond to the third objective that of how to identify and describe change within a system. Objective 3 seeks to not only describe changes within a system but it also aims to specifically use the constructs developed within resilience theory to map change and to then also apply this to the urban context.

In order to achieve this objective, it was broken up into two parts. These two parts are (1) identifying changes within a system and (2) describing the change that the system has undergone by using SES theory constructs. In both of these parts the translation and application of the resilience theory constructs to the urban system was shown.

The first part of this objective, to identify changes within a system, was achieved by first exploring the theory of how systems change. This was done by exploring the concepts of frozen accidents, gateway events and path dependency, which explain how specific events in a systems history can impact how the system changes and that by identifying such events one can better understand why a system is in its current path or trajectory.

In addition to looking at how past events shape the systems future resilience theory also argues that events at system scales above and below the focal system scale also impact on the focal system and are in tern impacted by focal system (Folke, 2006; Gunderson and Holling, 2001; Holling et al., 2001b). The theory of change, both at the focal scale and at the scales above and below the focal scale, was then included into the USDF, as shown in Figure 61.

As the properties of CAS are a constant of all CAS (Brownlee, 2007), the way that these properties present themselves within the same system at different points in the system's history allows for changes in the structure and behaviour of the system to be identified and described. This concept was included into the framework and by using the USDF as a means to describe the system at different points in time. In doing so one is able to identify how the behaviour and structure of the system has

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changed over time. The application of this was applied to the urban context by using the case studies of Irene and Lyttelton. The history of each neighbourhood was described and the changes identified at the focal scale, as well as the events at the scales at the higher and lower levels that impacted on the system. The changes were then summarised and presented in a timeline format.

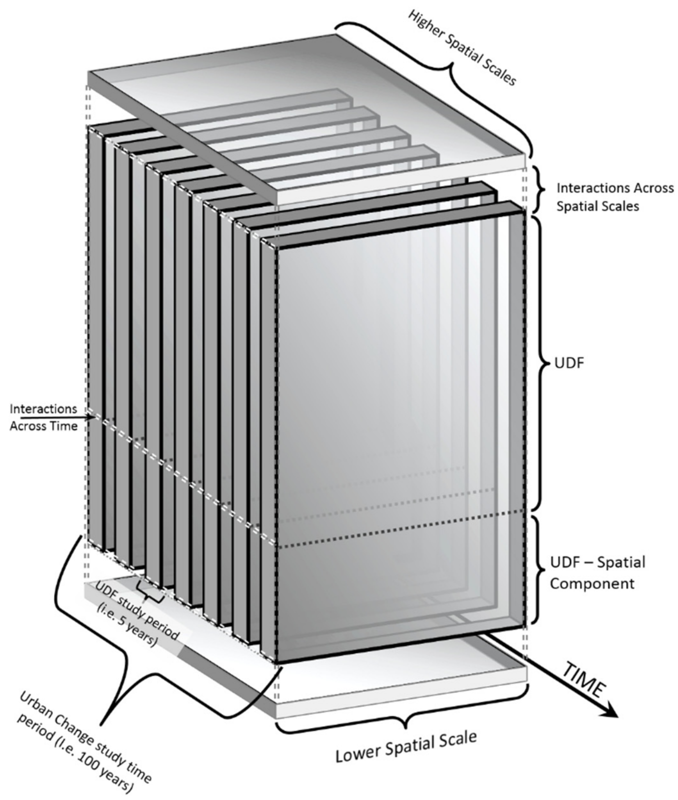

Figure 61: Addition of cross-scale interactions into the framework

The second part of achieving this objective requires that the change that the system has undergone be described by using SES theory constructs. To achieve this the concept of the *Adaptive Cycle*, taken from resilience theory, was used to describe the changes of the system. A systems behaviour can be described against the phases of the adaptive cycle. The adaptive cycle consists of four phases, namely; growth, conservation, release and reorganisation (Gunderson and Holling, 2001). Each of the phases of the Adaptive cycle has its own unique characteristics against which the changes in a system can be described and categorised. Each phase of the adaptive cycle is also characterised by varying levels of resilience (Gunderson and Holling, 2001).

When applying the adaptive cycle to the urban context, using Irene and Lyttelton as examples, the history and identified changes were viewed from the perspective the adaptive cycle and categorised in terms of each phase's characteristics. In doing so, the changes that the systems have undergone were plotted against the adaptive cycle and it was shown that Lyttelton and Irene have moved vary differently though the adaptive cycle. The adaptive cycle also makes it possible to compare different systems to each other.

7.2.4. Objective 4: To illustrate the application of the concepts to the urban environment.

The fourth objective of this study responded to the fact that the majority of tools and techniques within resilience and SES theory have been devolved for use in the study of ecosystems and not for the study of urban SES (Nel et al., 2013). This fact is important because if urban planners aim to achieve resilient cities, and if resilience assessments are to be done in the future, there is an urgent need to ensure that these assessments are able to be applied to the urban context.

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Throughout this study the application of complexity theory, SES theory and resilience theory was applied to the urban context by using various examples. Furthermore, in order to illustrate the full application of the framework presented within this study the examples of Irene and Lyttelton were used. This was done to provide consistency in how the framework can be applied as a full and integrated process. Where each step is reliant on the completion and understanding of the results of the previous. In doing so a more complete understand of the system can be created.

7.3. Limitations, contributions and further studies

"We cannot have complete knowledge of complex systems; we can only have knowledge in terms of a certain framework. There is not stepping outside of complexity (we are finite beings). This choice need not be arbitrary in any way, but it does mean that the status of the framework (and the framework itself) will have to be continually revised. Our knowledge of complex systems is always provisional. We have to be modest about the claims we make about such knowledge"

(Cilliers, 2005b, p. 259)

As show above, the study has met the goals that it set out to achieve. There are, however, some limitations that need mentioning. The terminology that is used within the CAS approach is built largely on systems thinking language. As a result, some of the terminology attached to the CAS approach has some of the negative connotations and stigma that is attached to system theory. This may make it more difficult to be accepted into some planning circles (Dovey, 2012, p. 357).

As planning is often seen as the management of change (de Roo et al., 2012; Innes and Booher, 2010; Rondinelli, 1973), many planners have spent much time and effort in creating top-down mechanisms to enforce, mitigate and manage change (Jacobs, 1961; Talen, 2008; Van Wyk, 2012). Whereas the traditional top-down approach seeks to implement control from above, a CAS approach seems to take the opposite approach. It suggests that planners have limited control over the system, due to the bottom-up processes involved (Holland, 1996), for the same reasons the long-term behaviour of CAS are near impossible to predict (Cilliers, 1998; Holland, 1992b).

What this means is that planners have limited real direct control over the system. Rather, in order to implement change, planners will require a better understanding of the system that they are working in. With that understanding they will be able to identify the leverage points with which they are able to help push, pull or nudge the system into the desired direction. The framework described within this study is seen as a tool to assist planners in understanding the system. After which it is up to the planner's discretion as to how one should appropriately intervene within the system.

An additional limitation of the CAS approach and the framework described within this dissertation is that it will not be able to describe the urban system fully, nor will it be able to describe all the possible changes that a system may undergo. It is, rather, a starting point for further exploration into complex systems, urban change and urban resilience. It provides a point of departure for the extraction and investigation of systems and how they change.

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The urban change framework described within this study makes an important contribution to the debate on urban resilience as well as urban change management by providing a practical means not only to describe a system, but also to identify and describe the changes that the system has undergone, thereby allowing the results of the framework to be used within existing resilience assessments. This framework adds to the current methodologies of doing resilience assessments while at the same time enables improved input into existing resilience assessments. This is becoming increasingly important as more and more governments, (national and local), NGO's and other institutions (i.e. the Rockefeller Foundation's 100 Resilient Cities Challenge) start to conduct resilience assessments. Furthermore, if we know whether a system is resilient (or not) and where it is on the adaptive cycle it may be possible to intervene within a system in an appropriate way in order to move the system into a more desirable state.

The framework may also be able to allow for the comparison of the rate and nature of change between various urban areas/systems, provided they are on the same spatial-temporal scale, as was done with Irene and Lyttelton. In doing so, the four phases of the adaptive cycle that describe an urban neighbourhood as shown in Table 20, can be tested, questioned and expanded on to determine if this provides an accurate description typical of the phases of the adaptive cycle for a neighbourhood, or if the example in the table is unique to Lyttelton and Irene.

While the framework described in this dissertation may enable urban planners to better understand how and why cities change. It should not be used to predict future change. Rather, it aims to place the user in a better position to anticipate, manage and respond to change by allowing them to determine where the system, or a part of it, is within the adaptive cycle. This implies crafting interventions in the system to be appropriate and not a 'one size fits all' approach.

Although this study demonstrates the usefulness of the proposed framework, its main objectives are to provide theoretical guidance to describe urban systems and how they change. As this study was primarily a theoretical exploration with limited practical examples, the effectiveness of the framework is still to be tested under different circumstances. Additionally, this study could not encompass the full detail in every aspect that may need to be considered. Future questions that need to be answered are whether or not the framework can incorporate aspects of 'ethics' and 'power' that are often associated with planning (Geyer and Rihani, 2010)? How the framework can incorporate changes in technology (hard infrastructure and information communication technology)? How changes in the natural environment will play effect the urban system? Should different rates of change, spatial scales and urban activities and functions be looked at the same way or do that need their own approaches? Can the framework assist in making meaningful and ethical planning related decisions?

As the case studies within this study were limited to two similar and inter-related areas, this limited the extent that the case studies could be used to test the framework. For this reason, it is recommended that further studies be undertaken by using the urban change framework to test the

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extent of the framework in various context. Such studies should include, but should not be limited to, studies within other metropolitan areas (within South Africa and internationally), rural areas, informal settlements/slums and areas with greater social-economic diversity, i.e. larger diversity in income, race, housing typologies, etc.

"I may not have gone where I wanted to go, but I think I have ended up where I intended to be"

Douglas Adams (1991) - The Long Dark Tea-Time of the Soul

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Annexures

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Annexure 1. Publications

This section provides a list of research that was used to test some of the concepts found within this dissertation. The section will provide the title, the book title or conference information (where applicable), the author of the research, the abstract and then the full citation for the research.

Title: Gating in South Africa: A gated community is a tree; a city is not

Book title: Beyond Gated Communities (2015)

Author(s): Darren Nel & Karina Landman

Abstract:

This chapter builds on the seminal work of Christopher Alexander, "A city is not a tree" and more recent work by the French architect/economist Serge Salat on urban morphology and urban resilience.

The chapter explores the urban form and structure of a number of gated communities in the eastern part of Pretoria in order to determine their impact on sustainable urbanism and in particular urban resilience. The aim is to identify whether gated communities typically resemble a tree-like structure (lattice) or leaf-like structure (semi-lattice), with the latter being more resilient over time according to recent studies. Gated communities are analysed according to a number of indicators for resilience, including connectivity, complexity, diversity, intensity and proximity and compared to an "open" neighbourhood, followed by a discussion of its implications for spatial transformation and the reconsideration of boundaries within cities.

In conclusion, the chapter then considers the relationship between gated communities and urban resilience in South Africa in the light of the statement that a gated community is a tree while a city is not.

Citation:

Nel, D., Landman, K., 2015. Gating in South Africa: A gated community is a tree; a city is not, in: Bagaeen, S., Uduku, O. (Eds.), Beyond Gated Communities. Routledge, London.

Title: A Gated Community is a Tree; a City Is Not

Conference: 7th International Conference for Gated communities and Private Urban Governances, Brighton, UK, 2013

Author(s): Darren Nel & Karina Landman

Abstract:

This paper builds on the seminal work of Christopher Alexander, "A city is not a tree" and more recent work by the French architect/economist Serge Salat on urban morphology and urban resilience. The paper will explore the urban form and structure of a number of gated communities in the eastern part

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of Pretoria in order to determine their impact on sustainable urbanism and in particular urban resilience. The aim is to identify whether gated communities typically resemble a tree-like structure (lattice) or leaf-like structure (semi-lattice), with the latter being more resilient over time according to recent studies. However, there may be additional factors influencing the transformation of urban form and structure over time and its impact on urban resilience. These include the nature of urban gating, the types of transitional spaces inside and outside these developments and the activities that take place within and in the surrounding areas. Given this, the gated neighbourhoods will be analysed according to a number of indicators for resilience, including connectivity, complexity, diversity, intensity and proximity. In conclusion the paper will then consider the relationship between gated communities and urban resilience in South Africa and reconsider the statement that a gated community is a tree while a city is not.

Citation:

Landman, K., Nel, D., 2013. A Gated Community is a Tree; a City is Not, in: Transitional Spaces and Appropriation Strategies (from the Point of View of Morphology, Architecture, Design and Political Sciences). Presented at the 7th International Conference for Gated communities and Private Urban Governances, University of Brighton, University of Brighton Moulsecoomb Campus, UK.

Title: Exploring the Relationship between Urban Morphology and Resilience in a few Neighbourhoods in Pretoria

Conference: 2nd National Urban Design Seminar, The Villa, Pretoria.

Author(s): Darren Nel & Karina Landman

Citation:

Landman, K., Nel, D., 2013. Exploring The Relationship Between Urban Morphology And Resilience In A Few Neighbourhoods In Pretoria, in: Spatial Considerations and Resilient Urban Form. Proceedings of the 2nd National Urban Design Seminar, The Villa, Pretoria.

Title: Exploring a Methodological Framework for Understanding Adaptive Change in Cities

Conference: 19th CIB World Building Congress, Brisbane, Australia, 2013.

Author(s): Darren Nel, Chrisna Du Plessis, Karina Landman

Abstract:

Resilience is about change and how systems respond to change. To understand resilience it is therefore important to understand how cities respond to change. Cities can be described as social ecological systems that react to change and perturbations through responses at various spatial and temporal scales. In the study of resilience of ecosystems, this is described through the concept of panarchy and the metaphor of the adaptive cycle. The adaptive cycle is used widely as a key metaphor to describe resilience. Central to this metaphor is the idea that systems undergo periodic cycles of change without fundamentally changing functional identity, remaining within a particular basin of

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attraction. However, internal or external pressures may also cause the system to tip into another basin of attraction or system state, with a different functional identity.

In ecosystems, these different states are well described and the characteristics indicating a change in identity are well defined. However, in the study of urban social ecological systems, this is still a mainly unexplored topic and the methodologies for identifying and mapping different urban system states and phases within the adaptive cycle, let alone the application of the adaptive cycle concept requires further investigation.

This purpose of this paper is to present a proposed a methodological framework for describing the movement of cities or neighbourhoods through the various phases of the adaptive cycle and possibly, different system states. This method is illustrated using the example of two neighbourhoods in South Africa and the changes they experienced over a period of approximately one hundred years.

Citation:

Nel, D., Plessis Du, C., Landman, K., 2013. Exploring a Methodological Framework forUnderstanding Adaptive Change in Cities, in: Kajewski, S., Manley, K., Hampson, K. (Eds.), Disasters and the Built Environment. Presented at the 19th CIB World Building Congress, Brisbane 2013: Construction and Society, Queensland University of Technology, Brisbane Convention Centre, Brisbane, Australia.

Title: Reconsidering urban resilience through an exploration of the historical system dynamics in two neighbourhoods in Pretoria

Conference: Planning Africa, Durban, South Africa, 2012

Author(s): Darren Nel & Karina Landman

Abstract:

In the on-going debate of sustainability and climate change urban resilience has become a key issue. Most of the literature pertaining to urban resilience has had a primary focus on the perspective of ecological resilience and or how to make the city system more resilient to things like a natural disaster (sudden shocks). With this regard the focus of the paper will be on the general resilience of the city, more specifically the sub-system of the neighbourhood.

A city is a specific system made up of a number of sub-systems. Resilience refers to the amount of change a system can experience before shifting to an alternative state with different structural and functional properties. Urban resilience is therefore concerned with the dynamics within cities and their relationships to the different sub-systems that constitute the whole, or in other words the distance between the existing urban system's state and the critical threshold that would force a collapse and total transformation of the existing system.

These changes that take place within cities are influenced by a range of components (spatial, social, institutional etc.) of the socio-ecological systems present in the urban environment. As a result of

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specific changes or urban dynamics, one or more sub-systems may be disturbed or disrupted, either temporarily or on a more permanent basis where the system change surpasses the critical threshold or breaking point and move to an alternative system state. As such specific urban sub-systems may be vulnerable to such changes and affect the larger system.

Citation:

Landman, K., Nel, D., 2012. Reconsidering urban resilience through an exploration of the historical system dynamics in two neighbourhoods in Pretoria, in: Spatial Planning: Promoting Resilience and Sustainability of Settlements. Presented at the Planning Africa Conference 2012, Durban, South Africa

Title: An Exploration into Urban Resilience from a Complex Adaptive Systems Perspective

Conference: Planning Africa, Durban, South Africa, 2012

Author(s): Verna Nel & Darren Nel

Abstract:

Resilience is defined as the ability to recover from a setback. It is also one of the attributes of a complex adaptive system. A system comprises a set of parts, entities or agents whose relationships determine the nature of their organisation. Information and energy flows are the key drivers of relationships that bind and constitute the system. Complex systems are non- linear and can be susceptible to small changes, but may also be capable of reverting back to a stable situation if perturbed. Complex adaptive systems are dynamic, open to their external surroundings, non-linear systems that are able to change, adjusting to novel environments. Thus complex adaptive systems are able to evolve while still retaining a large measure of stability. The nature of the information flows, the strength of the linkages and the degree of redundancy of individual agents or agglomerations (nodes) all play a role in the level of stability, responsiveness to change and hence longevity of the system.

Cities can be defined as complex adaptive systems, many of which have demonstrated great resilience over time, surviving wars, social unrest, economic crises and natural disasters. What are the attributes that have made such cities resilient while others have been unable to recover from a catastrophe or have faded into oblivion?

This paper begins to explore the concept of urban resilience from a complex adaptive systems perspective. It considers the elements that constitute the system, their relationships, and the nature of the flows into, within and from the system, as well as the patterns or agglomerations that describe it. It also examines the role of key agents or nodes within the system, which enable recovery, the importance of external and endogenous responses and how as well as the dynamics of reactions to crises.

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Citation:

Nel, V., Nel, D., 2012. An Exploration into Urban Resilience from a Complex Adaptive Systems Perspective, in: Spatial Planning: Promoting Resilience and Sustainability of Settlements. Presented at the Planning Africa Conference 2012, Durban, South Africa

Title: What Drives Spatial Change within a Neighbourhood? (Honours Dissertation)

Dissertation: Honours Dissertation. University of Pretoria. 2011

Author(s): Darren Nel

Abstract:

This research is aimed at identifying the drivers of spatial change within South African neighbourhoods. How neighbourhoods change spatially and what causes them to change has been investigated. Two case studies were undertaken of neighbourhoods within Tshwane that are in close proximity to each other but have developed very differently over the past one hundred years.

By consulting relevant literature and through an analysis of the neighbourhoods' histories and changes in spatial patterns it was found that no one specific factor causes neighbourhoods to change. It is rather a combination of forces working on and around the neighbourhoods in different ways that makes the difference in how they change and develop over time.

The findings of this research suggest that in the case of Lyttelton and Irene, the two case study neighbourhoods, the availability of water, location in relation to employment centres as well as the services and retail facilities that are in close proximity are amongst the biggest forces that have shaped these neighbourhoods.

Citation:

Nel, D., 2011. What Drives Spatial Change within a Neighbourhood? (Honours Dissertation). University of Pretoria, Pretoria.

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Annexure 2. Summary of characteristics of CAS by various authors

Below is a summary of the different characteristics, elements, properties and descriptions of complex adaptive systems as discussed by various authors. This is then summarised into a single 'general' description

Characteristics of Complex Adaptive systems as discussed by (Cilliers, 1998)

Characteristic	Description
Elements (Characteristic)	Complex systems are comprised of a large number of elements. – The more elements in the system the harder it becomes to give the behaviour of the system a formal description Each element in the system is only responsible for the information available to it locally and is ignorant of the behaviour of the system as a whole.
Interactions (Characteristic)	For a complex system to function, the elements must have **dynamic interactions** with each other. These **interactions happen and change over time**. The interactions need not be physical but can be a transferal of information. Elements in a system influence and are influenced by many other elements in the system. The behaviour of the system is not determined by the number of interactions of specific element but rather the way in which the interactions are carried out. The interactions of systems are **non-linear**. This non-linearity can result in large shocks having a small effect on the system, and vice versa. It is also a precondition for complexity Interactions are normally short in range, long range interactions are possible, however interactions can have a wide ranging influence, provided that interactions are rich, influence is quickly transferred from one neighbour to the next. This may result in the influence being transformed, improved or blocked. Some interactions may loop or **feedback** on themselves, directly or after a given interval. This feedback may be positive (enhancing) or negative (constraining). This aspect is called *recurrency*
Open to Environment (Characteristic)	Complex systems are open to their environment and are constantly interacting with their environment. It is this interaction with the environment and the openness of the system that often makes it difficult to determine the boundaries of the system. The scope/ boarder of the system is usually determined the purpose of the description of the system and is often influence by the position or the observer (world view). This processed of setting boundaries is called *framing*.
Non-equilibrium (Characteristic)	Due to the need for consistent flow of energy complex systems function under conditions distinctly away from equilibrium. For a complex system equilibrium is the equivalent to death
History (Characteristic)	When studying a complex system it is important to look at the systems history. This is because a systems past is partly the reason for its current behaviour
Evolution (Characteristic)	Systems evolve through time to suit their current environment. They learn, collectively, from the past.
Complex structures (Characteristic)	Each element within the system is unaware of the whole systems behaviour. If it was aware of that then it would have to have all of the complexity of the system in that element, this would be impossible as the 'consciousness' of the whole would be within that element. It is rather the richness of the interactions and the response of the 'simple' elements; to a limited amount of information accessible to them that builds the complexity of

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Characteristic	Description
	the system. When looking at complex systems we focus on the 'whole' instead of the individuals. The complexity of the systems is a emergent result of the complex structure and interactions of the individual elements.
Representation (Characteristic)	Complex systems must be able to collect **meaningful information** about its environment and store it for future use; this meaningful information must somehow *represent* **what is important for the continued existence of the system**. The representation of meaning within the system is done by the interactions and relationships between the structural components of the system itself. Meaning is a result of a process that involves elements from within and external to the system as well as the history of the system. Individual elements contain no particular representational 'meaning' on their own, it is rather the relationships and patterns (networks) thereof with other elements that create meaning
Self-Organisation (property)	**General attributes of self-organising systems**
	The structure of the system is a result of *interactions* between the system and its environment and *not* of a predetermined design. If there are changes to the environment of the system, the internal structure of the system can adapt dynamically to these changes, even if the changes are irregular
	Self-organisation cannot be described solely by the processes of feedback or regulation (these can be described linearly) but rather it involves higher order non-linear processes. It is an emergent property of a complex system as a whole (or large enough sub-system) and not of the individual elements, as they only operate on a local scale with 'short range' information and 'simple' rules. The macro level behaviour only emerges as a result of the micro or individual level interactions.
	Self-organising **systems increase in complexity** over time. This is because they have to 'learn' from experiences and have to 'store' or 'remember' past experiences in order to compare them with new ones. The more information or memories that can be stored, for comparison at a later stage, the better the 'decisions' it makes will be. Because systems increase their complexity over time they tend to age and at some point become saturated. As such self-organising systems have a history, a memory, however just as with humans systems also have a form of 'selective forgetting', and this means that information that is not used (or used often enough) is discarded. This process creates space for new information, slowing down the rate of saturation, and is also a form of measuring the importance of the stored information. The more something is used the more important the information is perceived to be. **Systems** can **remember** and **forget**.

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Characteristic	Description
	Self-organisation is not conducted or determined by specific goals, this makes it difficult to talk about a function of system of this nature. If we introduce the idea of a system having a *function* we run the risk of "anthropomorphising" or of providing an external reason for the inherent structure of the system (something we, the observer, are trying to avoid). However when the system is considered within the context of a larger system, the system being a sub-system of the larger one, can one talk about the function of the system. The idea of function is strongly linked to our description of complex systems. "The process of self-organisation cannot be driven by the attempt to perform a function; it is rather the result of an evolutive process whereby a system will simply not survive if it cannot adapt to more complex circumstances"(Cilliers, 1998). It is not possible to give a simplistic description of self-organising systems as the individual elements are not aware of the higher order pattern or behaviour, even though they themselves are the reason for this system manifesting in the first place. The different levels of a system cannot be given an independent description as they are essentially all interlinked.

Features of Complex Systems by (Innes and Booher, 2010)

Features	Description
Agents	A complex system is comprised of a large amount of individual agents that are connected through various networks
Interactions	The interactions between agents are dynamic, as they have local interactions where they exchange information and energy based on experiences/discoveries or "heuristics". Although agents may only have a short rage of interactions, i.e. with its immediate neighbours, the effects of these interactions move through the larger system. As a result of this complex systems have *memories* that are not located at any one specific place, but are rather distributed throughout the system.
Nonlinearity	The interactions between agents are nonlinear, iterative, recursive and are self-referential. There are many direct and indirect feedback loops between the various agents interactions
System Behaviour	The system is open to its surroundings The behaviour of the system cannot be determined by looking at the individual components, it is rather be interactions between the components that produce the systems behaviour. Comprehensible and unique patterns of order emerge from these interactions
Robustness and Adaption	Complex systems have both the ability to maintain their feasibility as well as the capacity to evolve. With enough diversity the "heuristics" (rule of thumb) will evolve as the individual agents adapt to each other. When this happens the system will reorganise its internal structure without the interference from an outside source or agent.

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Key concepts of complex systems as described by (Geyer and Rihani, 2010). They differentiate between physical, biotic and conscious complex systems. Although many of the ideas of each of these do overlap, there are differences between the various types of complex systems.

Key concepts of *Physical* Complex systems (Geyer and Rihani, 2010)	
Key Concept	Description
Limited compressibility and irreversibility	There is a difference between "physical orderly systems", "disorderly system" and "physical complex systems". – The most basic means to test this is to "examine the regularities in the system and the length of message needed to specify their occurrences in order to describe them"(similar to (Page, 2011) discussion of how to measure complexity). A *physical orderly system* is exceedingly regular; with a short *compressed* description of some of the recurring patterns or regularities is all that is needed in order to give a proper description of the system. A *physical disorderly system* has very little or no regularities, chaotic, which makes it very difficult if not impossible to describe A *complex physical system* lies between a physical orderly system and a physical disorderly system. It has regularities at can be summarised and compressed (limited compressibility) with some aspects that happen at random (incompressible). It lies between order and chaos. They are irreversible; meaning that the flow of time goes in one direction; that they alter themselves over time in unique ways that cannot be reversed or repeated (time is incredibly important). A complex physical system has a "past, present and future, and conditions are different at each phase". It is also important to note that the systems past effects the present and the future of the system to a more or less extent Looking for patterns and regularities is necessary but one observing the behaviour of individual elements will not lead one to understanding the behaviour of the system as a whole. It is also risky to make conclusions about the behaviour of complex systems from a limited number of occurrences. The fact that a complex system displays irreversibility also limits the amount that the system can be influence and its future behaviour predicted. When dealing with complex systems it is important to note that the systems past, *history*, plays an important role in its current and future behaviour. It is because of this that it is important to have a thorough understanding of the systems history as well as the systems 'culture'; the norms, values and conventions of that particular system.
Attractors	Attractors describe the probable long term behaviour of the system; they guide us in understanding how the system tends to behave (this also links to the culture of the system). Attractors, in orderly physical systems, are easy to describe. Examples of this are point and limit cycle attractors. Attractors are essential to understanding how systems are able to follow a particular, familiar, pattern and how they are then likely to radically and unpredictably change at the onset of a small perturbation within the system and then move into a new basin of attraction with new and unpredictable behaviours.
	Various types of attractors:

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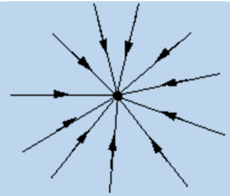
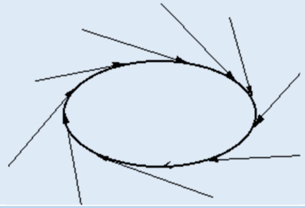
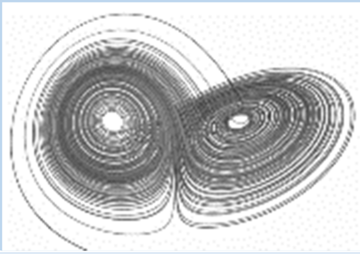
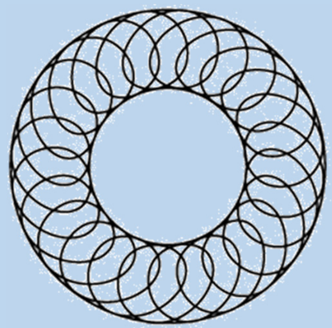
	Point Attractor I.e. A pendulum swinging It goes through different states as the motions gradually drain into the 'basin of attraction'. The system will eventually come to rest at the 'point' Occurs in an orderly physical systems Motions are predictable	
	Limit-cycle Attractor I.e. A frictionless pendulum in a vacuum Attractor looks like a segment of a circle that encases all possible states that the pendulum may take Occurs in an orderly physical systems Motions are predictable	
	Strange Attractor System contains both positive and negative feedback – basins of attraction are called strange attractors They don't have regular symmetrical shapes, due to the interactions of positive and negative feedback Small changes in initial conditions can lead to a large change in the systems course, This is then followed by the systems taking on different states	
Local Interactions, connectivity and simple rules	Complex systems have **many internal elements** that interact with each other to 'create' the overall pattern of the system, as seen by an outside observer. **Local interactions** of the system become increasingly important since small events at this level can have large effects. The connectivity between agents allows for the system to self-organise; under a "*basic framework of simple rules* of interaction"(Geyer and Rihani, 2010)	
Local variety and global stability	The conditions that a system functions under oscillate and can only be determined within a varied range of probability. This means that the system may assume a varying number of states at different points in time. This allows for '*local variety*'; meaning that the system can move within an acceptable range within the limits of the attractor. The assortments of states that differ within the attractor basin gives the system '*global stability*' under a varying environment. This type of behaviour is often found in *torus* attractors, often found within population dynamics. This type of attractor allows for small amounts of variation without moving the system into a new attractor basin. However, positive feedback may cause these small variations to become major transformations at specific 'tipping points' an move the system into a new global pattern. A system that appears stable may, at any time and for no apparent (immediately observable) reason begin exhibiting a new pattern of behaviour. This is because there is rarely a direct link between cause and effect.	

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Non-linearity	Non-linearity can be seen as the outcome of many of the previous elements working together. Complex systems do not display orderly behaviour as such their behaviour cannot be predicted in a linear manor; as seen with many top-down, reductionist or determinist, approaches to socio-economic situations
Key concepts of *Biotic* Complex systems (Geyer and Rihani, 2010)	
Adaption, survival, variety and 'good enough'	Success in **adaption** depends on three things. The system must assess its environment – **Learning** The system must act on the gathered knowledge – **Response** The system must **survive** long enough to repeat the process Basically survival of the fittest comes down to survival of the most adaptable and stable. Among the difficulties of observing adaption in the real world is the time between these cycles (this is where computer models are useful as they can simulate these cycles at a faster rate). From simulations what often come out is that **variety** is an essential factor for survival. Whats important to note is that "evolution does not lead to an optimal end-state. 'Good enough' seems to be the sum total of what nature hopes to achieve, successful evolution being an ongoing open-ended process of often small, effective adaptions" (Geyer and Rihani, 2010). From this it is important to note that end-state planning, when involving complex adaptive systems, like humans, are associated with the search for "an 'end' to the process of human society are exposed as utter nonsense" (Geyer and Rihani, 2010).
Evolution	Biological system adapt by having, at all times, some elements that are able to deal with the new environments that the system may encounter. The system must then survive long enough to be able to adapt again, this is a very cyclic process. If one considers the second law of thermodynamics: when things are left on their own, they move to a state of disorder, decay or chaos. For this to be 'prevented' a system requires a continual energy and action; in order to maintain a stable, less probable state of survival which should lead to evolution. However is to little energy or effort is given then the system will move to a state of chaos but if too much energy or effort is given the system will be 'killed' by too much control and order, it will remain static. Living complex adaptive systems must remain in the realm between order and chaos in order to survive and adapt.
Punctuated equilibrium, gateway events, and frozen accidents	Biotic complex systems tend to stay very much the same for a relatively long stretches of time but then undertake periods of rapid, 'radical' change. "This pattern of large upheavals separated by long periods of global stability, but energetic local activity is referred to as *punctuated equilibrium*"(Geyer and Rihani, 2010) (similar to Gunderson and Holling's (2001) Adaptive Cycle and the Panarchy models). These changes may come and go without leaving any real trace but every now and then a small 'shock' can move the system into another attractor without any warning. **Variety/diversity** allows the system to be more 'flexible' and move with the changes (diversity adds to resilience) In evolution, 'chance' events from the past can become an underlying part of that system from that point on. These are called *frozen accidents*. Once a frozen accident has occurred the system is inadvertently set on a particular path (history matters – path dependency or 'Lock-in' (Martin and Sunley, 2006)). The accumulation of frozen accidents may case more general regularities to form. "in our human world, this combination of frozen accidents and regularities can easily been seen in the current structure of many of our major institutions" (Geyer and Rihani, 2010). What is typical of all biotic complex systems is this continual contest between the conservative influence of frozen accidents and the adaptability of emerging regularities. Gateway events are things that happen from time to time and create new and unexpected opportunities, for some, and disaster, of others, within the system. A gateway event may be a new innovation within the system. Gateway events, like frozen accidents, are also a big contributor to the creation of pattern of punctuated equilibrium. A "system, individual, group or nation must have sufficient variety and flexibility to survive the shock of the latest gateway event in the first instance before it could proceed to profit from the new opportunities on offer" (Geyer and Rihani, 2010).

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Arrow of time and depth	Time, in complex systems, moves on one direction only, from past to present to the future. The system, and its patterns, is a product of its past up until that point. As the system goes through time many small and some large changes occur. As this happens frozen accidents accumulate as regularities that move the system into a direction that might create new gateway events. Because of this predicting the future of the system become increasingly difficult as complex systems cannot 'redo' what has happened as this will produce a new/different result than that which was originally taken. Biotic complex systems tend to become more complex as they move through time, the more complex they are the more complex they tend to become. It is only a tendency for more complex systems to become more complex they can become lexx complex. The increasing complexity happens as the different layers of interconnections and adaptions build up. This must happen at a rate the system can manage and cannot be speeded up significantly or artificially. Systems need time to generate a sufficient amount of *depth* in complexity. Systems with greater depth have no guarantee of surviving; however the tendency is for the more divers and adaptive systems to survive.
Key concepts of *Conscious* (human) Complex systems (Geyer and Rihani, 2010)	
Bounded freedom and Diversity	Consciousness gives us, humans, a greater degree of freedom, in comparison to biotic systems. Consciousness had given us the ability to be aware of and control our surroundings as we have the capacity to gather information, communicate it and interpret that information. This freedom allows us to go beyond the limits of our genetic limitations and needs. It gives us the ability to act individually or collectively. Genetic mutation, natural selection, competition, reproduction and survival help to enforce diversity and adaption on biotic complex systems. However what makes human diversity and adaptability unique is the ability to store, communicate and interpret information. Humans are biologically not very divers but these unique abilities of ours lets us diversify our behaviour/actions and increase the speed at which we adapt to our environments. Too much diversity can be a bad thing as we would all have our own agendas, language, etc. as such we need some form of commonalities or *boundaries*, am *evolving societal framework* to guide or bind our actions otherwise all human behaviour would be like random noise and would not be able to create any form of emergent, stable, patterns.
An evolving societal framework	The *evolving societal framework* can be seen as the "accumulation of frozen accidents and regularities in human development that has a tendency to become more complex with time"(Geyer and Rihani, 2010). The growth of evolving societal framework and conscious complexity has three costs: With increasing independence from biological constraints comes an increasing dependence on social norms, beliefs and customs in order to maintain our complex human system. With the growth of civilisations and the development of better transport, developing societies started to become increasingly dependent on interactions with other societies. In spite of the trend of human systems to increase their complexity there has been a consistent pattern of maintaining an elite rigidity. As civilisations and societies become increasingly complex and social groups more stratified, the elite have tended to develop means to maintain their dominate positions. There is always a tension in human complex systems to have a strain between rigidifying elites and standard social complexity and chaotic interactions.
Emergence and unpredictability	Because of the complexity and the emergent behaviour thereof the evolution of the human system is incredibly open. This openness and consistent adaption also means that human systems are non-linear and are unpredictable. This openness does not mean that everything is chaotic; we can over the long term predict some fundamental things with a high degree of accuracy. This is also true for some detailed things in the short term. There are two dangerous things that this limited predictability have created: The belief in a/the 'core' and the ability to copy the new model.

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	The belied that the new 'final' model can be found and copied These concepts, and the failure of them, have been true in many countries that have tried to copy another countries economic model to no success. Among the problems with these ideas, from a complex systems perspective, is that each system that is being copies has its own emergent properties and form of unpredictability that cannot be copied.
The limits of knowledge and importance of learning	Predictability of system behaviour, from a reductionists and not a complexity approach, relies on the systems stable global properties instead of focusing on the details of what is happening within the system (these details give the clues about the appropriate actions to be taken to have the desired results). Complex systems do not respond well to command-and-control methods; which, when applied with enough force, may produce short term success but are not sustainable over the long term. These systems instead respond better to a 'light-touch' style of management which entails constant monitoring of the overall performance and patterns of the system and making small careful, incremental, adjustments when needed. For complexity there is no limit to the amount of knowledge that can be contained within the system as this is an emergent feature of the complex system. Tis also implies that the importance of learning, as a process for the system instead of an endpoint to be achieved. Learning, as with adaption and variety/diversity, fundamentally a property of a complex human system. Learning allows us to go beyond our biotic limitations

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Components and Characteristics as discussed by (Page, 2011)in his book *Complexity and Diversity*

Component /Characteristic	Description
Complexity (property) (p 24 - 36) System	Complexity is created from the **interactions of elements** that create a new behaviour. The underlying complexity of the system can create a higher order emergent behaviour in that system. A complex system's behaviour is greater than the sum of its parts. An increase in the diversity of the systems elements can cause an increase in the complexity of the system. Complexity can be created from simple rules. Complexity can be described in three ways (Page, 2011): *Complexity lies* ***B****etween* ***O****rder* ***A****nd* ***R****andomness* – **BOAR** *Complexity cannot be easily* ***D****escribed,* ***E****volved,* ***E****ngineered, or* ***P****redicted* – **DEEP** Complexity lies at the edge of chaos. [Chaos refers to being sensitivity to initial conditions while randomness refers to unpredictability]
Diversity (p 16 -24)	Complex systems are comprised of a diverse arrangement of elements that are interacting with each other to produce an emergent behaviour. Diversity can be described in three ways(Page, 2011): **Variation** – Diversity within type. The differences in the amount of an attribute or characteristic. I.e. the difference in the height of the population **Diversity** – Diversity of types or kinds. The differences in the kind, I.e. the different kinds of cars **Composition** - Diversity of composition. The differences in the way that the things or types are put together or arranged. I.e. molecule Diversity, or rather varying amounts and configuration of the different types of diversity within the system can contribute to an increase in the complexity of the system. However, "*fundamental diversity* is not required for complexity. *Emergent diversity* is"(Page, 2011)
Emergence and Interactions (p 25 -27, 41 - 45)	Emergence, in complex systems, is higher order functions, properties or structures that occur from the **interactions** of the different entities. An example of this would be that complex adaptive systems have and emergent robustness or resilience.
Robustness (p 149, 196 - 248)	(Page, 2011) differentiates between robustness, stability and resilience: **Robustness** is the ability of a system to maintain its functionality under change or perturbations, internal or external to the system. **Stability** is the tendency for the system to return to equilibrium (dynamic equilibrium) under a dynamic. **Resilience** is the ability of the system to respond to and recover from a sock Robustness of a system refers to a systems ability to maintain its functions under varying environments as well as the "ablity of the system to flourish"(Page, 2011). Robust systems do not have to go back to a previous equilibrium after a disturbance, instead they 'move' to a new equilibrium. They do this by changing to their environments. The idea of robustness "captures day-today sustainability as well as responsiveness to shocks…it expands on the notion of resilience, which considers the ability of a system to respond to and recover from trauma"(Page, 2011). Robustness can also refer to the entities/agents that are contained within that system and the system as a whole. (Page, 2011) describes some of the things that contribute to a systems robustness. Specialisation 1: Comparative Advantage Specialisation 2: Learning by Doing

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	Responsiveness Synergies 1: Superaddictive Tricks Synergies 2: Multiple Landscapes Synergies 3: Diversity Production Collective knowledge Redundancy and Degeneracy Firewalling and Modularity Cross Cutting Cleaverages

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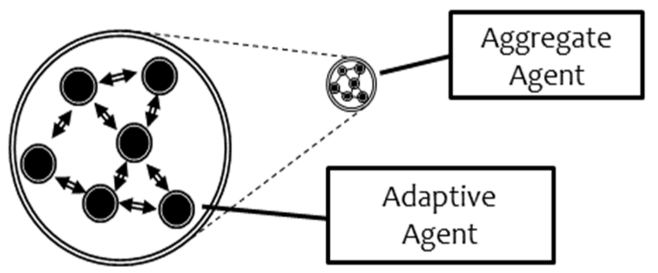
Components and Characteristics as discussed by(Holland, 1996) in his book *Hidden Order*

Characteristic	Description
Agents, Meta-Agents and Adaption	Complex adaptive systems are made up of large amounts of active **elements** or **agents** (agents are *active* elements) that **interact** with each other. These agents are divers in form and ability. An agent's behaviour is determined by a set of rules, i.e. stimulus response rules (IF *s* happens THEN respond with *r*). These rules are used to begin to describe agent strategies. **Agents adapt** by changing the rules that they use as they gain experience and in response to adaptions made by other adaptive agents within the system. This continues adaptions that are made create complex **temporal patters** that are found in complex adaptive systems.  Adapted from Holland (1996) Agent's individual abilities need to be described in order for us to start to understand the interactions between large numbers of agents. From this point we can begin to understand the consistently changing patterns of behaviour that are generated by complex adaptive systems Holland (1996, p 6) outlines two types of agents found in complex adaptive systems, namely: Adaptive Agents and Aggregate Agents. **Adaptive Agent**: Complex adaptive systems are made up of large amounts of agents. Agents are *active* elements. **Aggregate Agent**: The systems behaviour depends on interactions of the individual agents. Aggregated agents are a 'cluster' of agents that aggregate together to form a meta-agent. These aggregated agents may aggregate again to form a higher hierarchal level.
(Holland, 1996) describes four properties and three mechanisms that are the characteristics of complex adaptive systems, they are:	
Aggregation [Property] (Holland, 1996)	Aggregation in a complex adaptive systems (cas) can be viewed in two ways; 1. how do we model cas and 2. What do cas's do. In order to begin to model cas one must first find a standard way of simplifying complex systems. Essentially we being to create different categories into which group similar things and then treat these categories as comparable. In creating these categories we decide which details are not needed for answering the question of interest, and then proceed to ignore them. We then put the relevant things into categories. These categories them become the building blocks of the model. The second way to view aggregation is that from the perspective of the emergence of large-scale, complex, behaviours that occur from aggregate interactions of less complex agents. Aggregates formed in this way can then become adaptive agents and from higher level aggregate agent, meta-agent (first sense). If this process is repeated a second time (second sense), or more, then one starts to find the hierarchical organisation that are typical of complex systems. Aggregation in the second sense is a basic characteristic of all complex adaptive systems.

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Tagging [Mechanism] (Holland, 1996)	Tagging is a widespread mechanism for the formation of aggregates. It acts as a means of boundary formation by facilitating selective interactions within a cas. Cas use tags to manipulate symmetries and ignore some details while bringing our attention to others. Tags allow us to see and take action on things previously hidden by symmetries. Tags allow agents within a cas to select amongst agents or objects that would normally be invisible or indistinguishable. Well established tag-based interactions create a basis for a cas to filter information, specialise and cooperate. Further tagging allows for meta-agents and organisations to emerge, even though their components are consistently changing.
Nonlinearity [Property] (Holland, 1996)	Cas are nonlinear. They are more than the sum of their parts. One cannot approach a cas by adding the *sum* or average of its individual parts. It is rather the **product** of the distinct variables that helps us describe the cas. Aggregating (categorising or grouping) some variables help to simplify the calculations needed to describe the nonlinear equation for a cas. “nonlinear interactions almost always make the behaviour of the aggregate more complicated than would be predicted by summing or averaging” (Holland, 1996).
Flows [Property] (Holland, 1996)	Flows in a cas move over a network of nodes and connectors that vary over time. Nodes are the processors, agents, and the connectors that provide the possible interactions for the cas. As such we can say that cas have [node, connector, resource] movements. The flows and networks are never set in time because nodes and connectors may form or vanish as the agents within the cas adapt, or fail to do so. As a result the patterns that form are a reflection of the changing adaptions that happen over time as the system gains experience. Tags in a cas often describe the network by defining the major/critical connections. Tags take on this role as the adaptive process transforms a cas opts for tags that encourage useful interactions and discourages the tags that break down connections. As such the useful tags spread and the disruptive tags taken out of the system. Flows have two properties: **The multiplier effect**: The multiplier effect arises if one introduces an additions resource, for example, at a particular node. The general trend is that this resource will be passed on from node to node, with the possibility of the resource being transformed as this happens. Essentially the effect of the resource is multiplied as it moves from node to node. The multiplier effect occurs regardless of the nature of the resource and is a key feature of a network, and the flows within it. The idea of the multiplier effect is useful when the effect of a new resource, or the deviation of an existing one, wants to be estimated. The multiplier effect is increasingly apparent when evolutionary change happens; this hinders our ability to use simple trends for long-range predictions. **The recycling effect**: This uses cycles, and the effect thereof, within the network to recycle and reuse some of the resources within the system at various nodes. This produces more resources, with the same input, at each node which then translates into more output. The recycling effect can have a large effect on the overall system when many cycles of recycling have been done.
Diversity [Property] (Holland, 1996)	The fact that diversity within a cas is not accidental or random. The endurance of any particular agent is reliant on the context that other agents within the cas. Each type of agent finds a particular ‘niche’, which it is prescribed to. This is through the interactions converging on that agent. If that type of agent is removed from the cas the system will respond, through various adaptions, to fill the gap that has been left by that deleted agent. Although the new agent may not be an exact ‘replica’ of the agent that it is replacing, it will fulfil the same role or function. Diversity within a cas also comes about when the distribution of an agent creates a new niche (creation of new prospects for interactions) to be exploited by the system or rather the adaption by other agents within that system.

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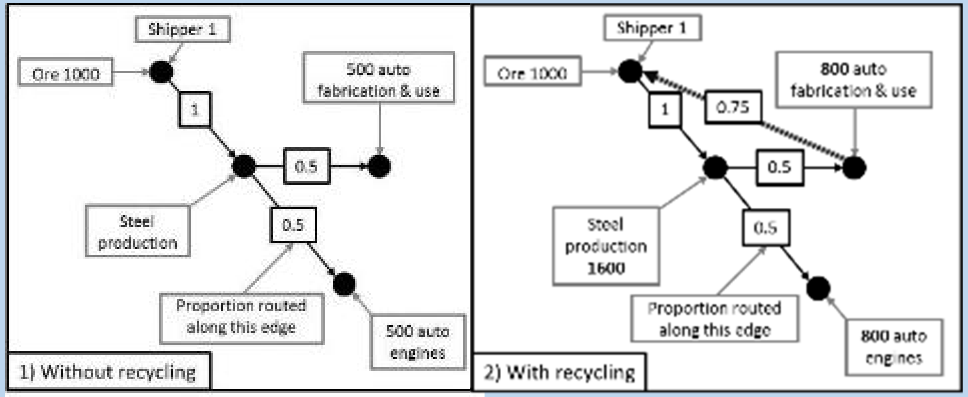
	Diversity within a cas is a dynamic, ever changing pattern. Which, if the interactions are disturbed though the deletion of an agent, will restate itself even though the new agents may differ, in detail, from the old agent. The important thing is that patterns within a cas are continuously evolving through ‘progressive adaptions’ which intern create the opportunity for new interactions and niches to form. A cas that uses cyclic flows allows the system the retain resources. The retention of these resources allows the system to exploit new niches by new types of agents. The parts of a cas that fully utilise these opportunities, especially the ones that increase recycling within the system, will ultimately flourish. While the parts that don’t use the opportunity will lose their resources to those which do. Through the process of increasing recycling greater diversity will be achieved within the cas. The nonlinearity of a cas, coupled with the recycling of resources by the aggregate behaviour of a diverse range of agents, is greater than the sum of the individual actions. Continued novelty is the defining feature of a cas. 
Internal Models [Mechanism] (Holland, 1996)	An internal model in a cas is a mechanism for anticipation or prediction. The simple process for creating models is the eliminate details so that selected patterns are emphasised. However for internal models the models are located within the agents, as a result the agent must select the patterns from all the incoming information that it receives and then use the patterns to make changes to its internal structure. These changes should allow the agent to anticipate the consequences of those changes when the agent comes across that pattern again. There are two types of internal models, namely tacit and overt. Both internal models are found in cas. Tacit: “A tacit internal model simply prescribes a current action, under *implicit* prediction of some desired future state” Overt: “An overt internal model is used as a basis for *explicit*, but internal, explorations of alternatives, a process often called *lookahead*” (Holland, 1996) In order to differentiate an internal model of an agent from the other parts of its internal structure we can look at one of the critical characteristics of a model. “a model allows us to infer something about the thing modelled… a given structure in an agents is an internal model if we can infer something of the agent’s environment merely by inspecting that structure” (Holland, 1996). To add to this, in order to rule out inanimate objects, the structure of the agent that informs us about the agent’s environment must also actively determine the behaviour of the agent.
Building Blocks [Mechanism] (Holland, 1996)	The mechanism of building blocks is essentially the process of deconstructing a complex scene into simpler parts, these parts need not be simple they may in fact be complex in their own way. However they may be put into already recognisable, reusable and tested ‘compartments or categories’ that have been created through natural selection or learning. The different parts can be used and reused in different ways and combinations. The combination of these different building blocks can result in a complex environment. The advantage of creating and using building blocks is that if “we can reduce the building blocks at one level to interactions and combinations of building blocks at a lower-level: the laws at the higher level derive from the laws of the lower-level building blocks” (Holland, 1996). Building block are a widespread phenomenon of all internal models and a feature of a cas

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Annexure 3. Summary of characteristics of complex and CAS by various authors

Summary of characteristics of complex and complex adaptive systems by various authors											
Cilliers (1998, 2008)	Innes & Booher (2010)	Geyer and Rihani (2001, 2010)	Page (2011)	Holland (1996, 1998,2006, 2007,2012)	(Hillier in de Roo et al., 2012, Kindle location 1037-1835)	de Roo in de Roo and Silva (2012, Kindle Location 692-1111)	Health Foundation (2012)	Roggema (2012)	Nel (2009)	Johnson (2002)	Portugali (2011)
Elements	Agents	Adaption, survival, variety and 'good enough'	Complexity (property)	Agents, Meta-Agents	Multiplicity (Comprised of various parts)	Co-evolution	edge of order and chaos	Adaptive capacity	edge of order and chaos	Adaptive	edge of order and chaos
Non-linear Interactions	Emergence	An evolving societal framework	Diversity	edge of order and chaos	Adaption	Emergence at the edge of order and chaos	Co-evolution	Agility	Adaptive	Agents	Dynamic (time is impotant)
Open to Environment	Non-linear Interactions	Arrow of time and depth	Emergence and Interactions	Adaption	Assemblages (Aggregation)	Evolution	Elements	Co-evolution	Agents	Emergence	Emergence
Non-equilibrium	Non-linearity	Attractors	Robustness	Aggregation	Connected elements	path-dependency	Evolution	Coexistence	Attractors	Non-linear Interactions	fractals
History/frozen accidents	Open to Environment	Bounded freedom and Diversity		Building Blocks	Diversity	Self-Organisation	Nested systems	Diversity	Emergence	Self-organisation	Learning and memory
Evolution	Robustness and Adaption	Emergence and unpredictability		Decomposition	Emergence	systems are open	Non-linear Interactions	Emergence	fractals		Networks

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Summary of characteristics of complex and complex adaptive systems by various authors											
Complex structures	Self-Organisation	Evolution		Diversity	Folding		Open to Environment	Flexibility	Hierarchies		Self-organisation
Representation	System Memory	Limited compressibility and irreversibility		Emergence	Immanence/ Emergence		Requisite variety (diversity)	Resilience	Non-linearity		Sensitive to initial conditions
Self-Organisation		Local Interactions, connectivity and simple rules		Flows	Non-linear Interactions across a network		Self-Organisation	Robustness	Self-organisation		
Hierarchies		Local variety and global stability		Internal Models	Open to Environment		Simple rules	Self-healing	Sensitive to initial conditions		
		Non-linearity		Learning and memory	Self-Organisation			Self-organisation	Systems have history		
		Punctuated equilibrium, gateway events, and frozen accidents		Tagging	Time and trajectories			Vulnerability			
		The limits of knowledge and importance of learning									

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Annexure 4. Definitions of complex systems by various authors

Definitions of a complex system by various authors

Definitions by Various Authors	Key Concepts	Source
Complex systems		
"a complex system is a system of many dynamically interacting parts or particles. In such systems the micro-level interactions of the parts or particles leads to the emergence of macro-level pattern of behaviour "	Many interacting parts (agents) Interaction of parts creates larger behaviour	(Beinhocker, 2006)
"A complex system is not constructed merely by the sum of its components, but also by the intricate relationships between these components"…	Relationships between components	(Cilliers, 1998)
"A complex system is comprised of a large number of non-linearly interacting non-decomposable elements."	Many elements Non-linear interactions Non-decomposable elements	(Richardson, 2005a)
Complex systems have "numerous internal elements; dynamic, because their global behaviour is governed by local interactions between the elements; and a dissipative, because they have to consume energy to maintains stable global patterns"	Numerous elements (agents) Dynamic Dissipative (need constant input of energy) Stable global patterns	(Geyer and Rihani, 2010)
"Complex systems are collections of divers, connected, interdependent entities whose behaviour is determined by rules, which may adapt, but need not. The interactions of these entities often produce phenomena that are more than the parts. These phenomena are called emergent"	Collections entities (agents) Entities are divers, connected and interdependent Entities follow rules Rules can adapt Interaction of entities create emergent behaviour	(Page, 2011)
Complex adaptive systems		
"a complex system is a system of many dynamically interacting parts or particles. In such systems the micro-level interactions of the parts or particles leads to the emergence of macro-level pattern of behaviour….Scientists refer to parts or particles that have the ability to process information and adapt their behaviour as agents and call the system that agents interact in complex adaptive systems"	Many parts Dynamic interactions Small interaction create emergent behaviour Agents adapt individual behaviour	(Beinhocker, 2006)

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Definitions by Various Authors	Key Concepts	Source
A complex "system is made up of very large numbers of individual agents connected through multiple networks. Second, these agents interact dynamically, exchanging information and energy according to localized heuristics….the system has memory that is not located at any one place. Third, the interactions are nonlinear, iterative, recursive, and self-referential with many direct and indirect feedback loops. Fourth, the system is open to its environment, and its behaviour is determined by the interaction. Fifth, the system displays both the capacity to maintain its viability and the capacity to evolve. With sufficient internal diversity, the heuristics for action will evolve, the agents will adapt to each other, and the system can reorganize its internal structure without the intervention of an outside agent"	Many elements Connected through network Dynamic, non-linear, iterative, recursive, self-referential interactions Local information/ energy exchange System has memory System is open to its environment System evolves Agents adapt and not system Internal structure can change	(Innes and Booher, 2010)
"A complex system consists of divers entities that interact in a network or contact structure…These entities' actions are interdependent… entities [within a complex system] follow rules" …"complex adaptive systems – systems in which the entities adapt…Adaption occurs at the level of individuals or of types. The system itself doesn't adapt. The parts do; they alter their behaviours leading to system, level adaption"	Divers elements Elements interact Network CAS follow rules Elements adapt & not system	(Page, 2011)
CAS "have many autonomous parts, they are able to respond to external changes and form self-maintaining systems with internal feedback paths. The essence of CAS is that they self-organize, to optimize function."	Many elements Respond to external change Feed-back Self-organised	(Lucas, 2006)
Cas are "systems composed of interacting agents described in terms of rules. These agents adapt by changing their rules as experience accumulates. In cas, a major part of the environment of any given adaptive agent consists of other adaptive agents, so that a portion of any agent's efforts at adaption are spent adapting to other adaptive agents. This one feature is a major source of the complex temporal patterns that cas generate"	Interacting agents Agents adapt (not the system) Agents follow rules Rules can adapt Agent's adapt to other agents Adaption creates complex temporal patterns	(Holland, 1996)

[Note: When talking about the individual 'things' or components that make up a system some authors use the term *agents* while others prefer to us the terms *elements*, or *entities*. These terms are interchangeable. However, for consistency, the term "agent" will be used in this study]

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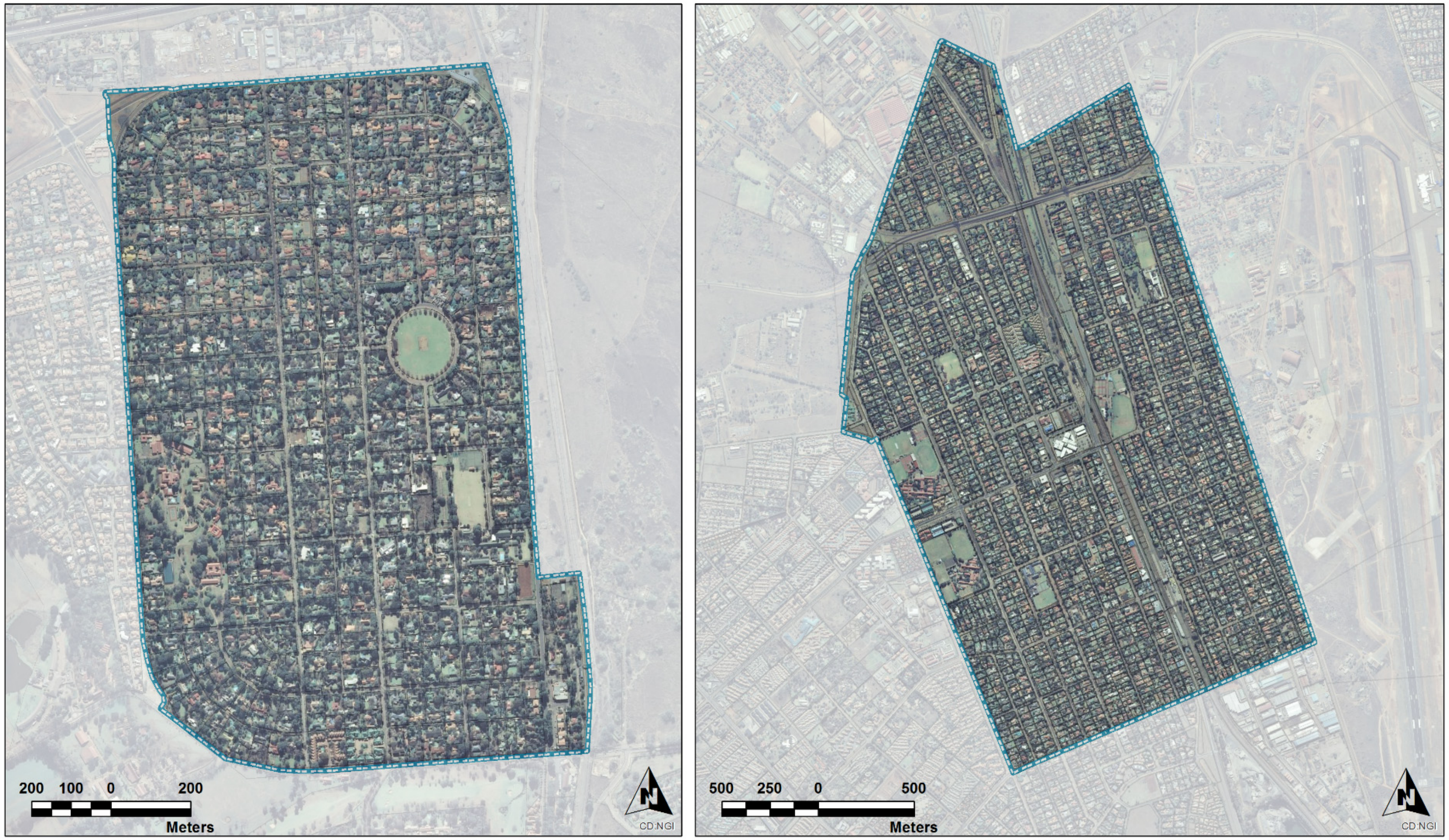
Annexure 5. Additional information on Irene and Lyttelton

Aerial photo of Irene (left) and Lyttelton (right) with the land parcels. Additionally the spatial boundaries for the two areas is also shown

Aerial Photo (Image source NGI 2014)



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The images blow shows the land parcels for Irene (left) and Lyttelton (right).

Land Parcels (Source City of Tshwane 2013)

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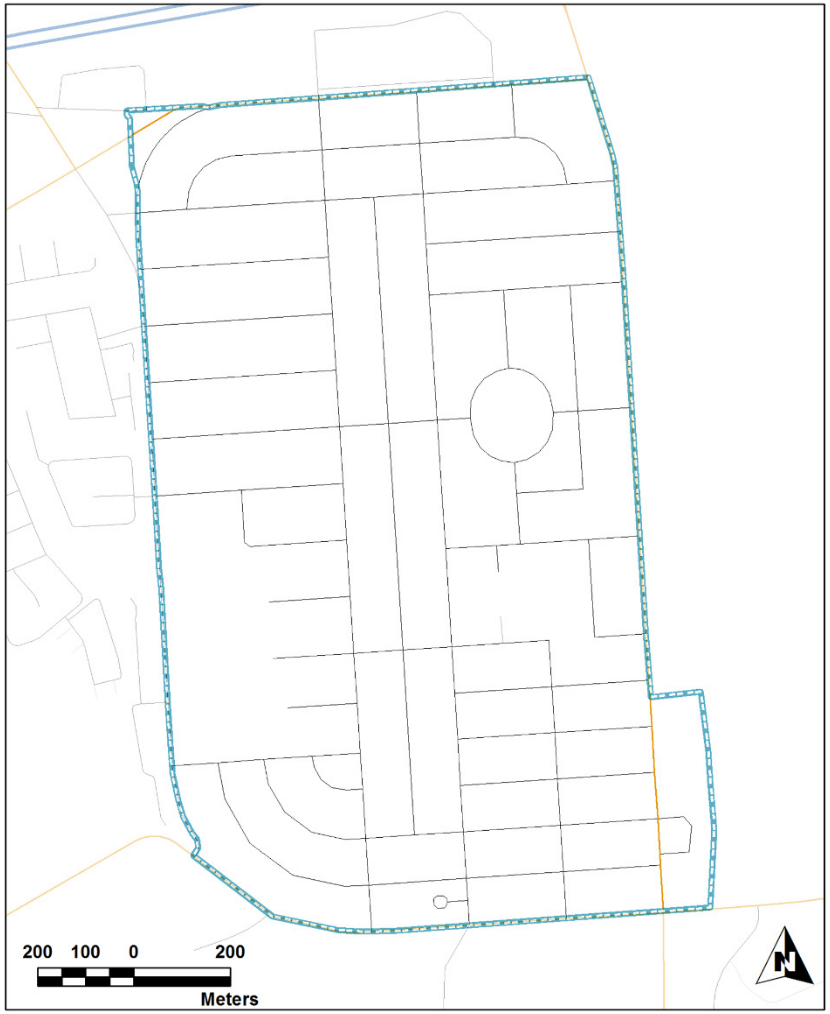
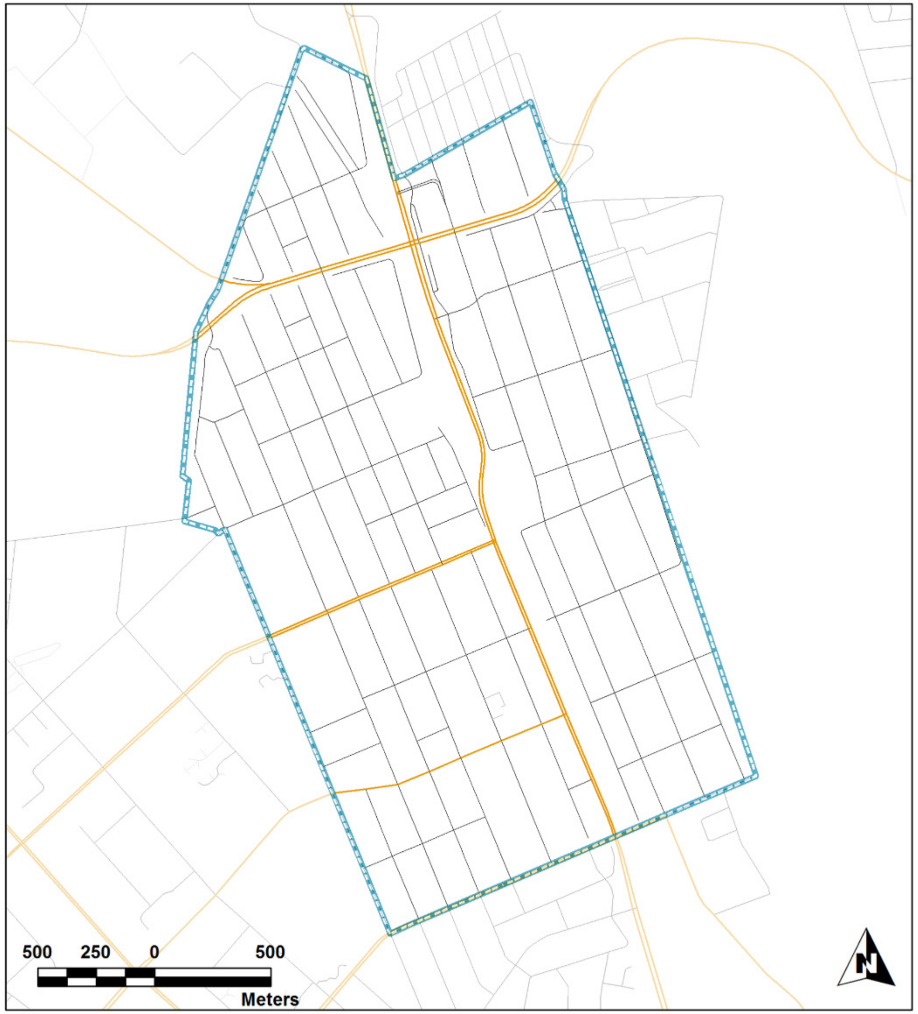
The road transportation network for Irene (left) and Lyttelton (right). The orange lines indicate the higher order roads

Transportation Network (Source City of Tshwane 2013)





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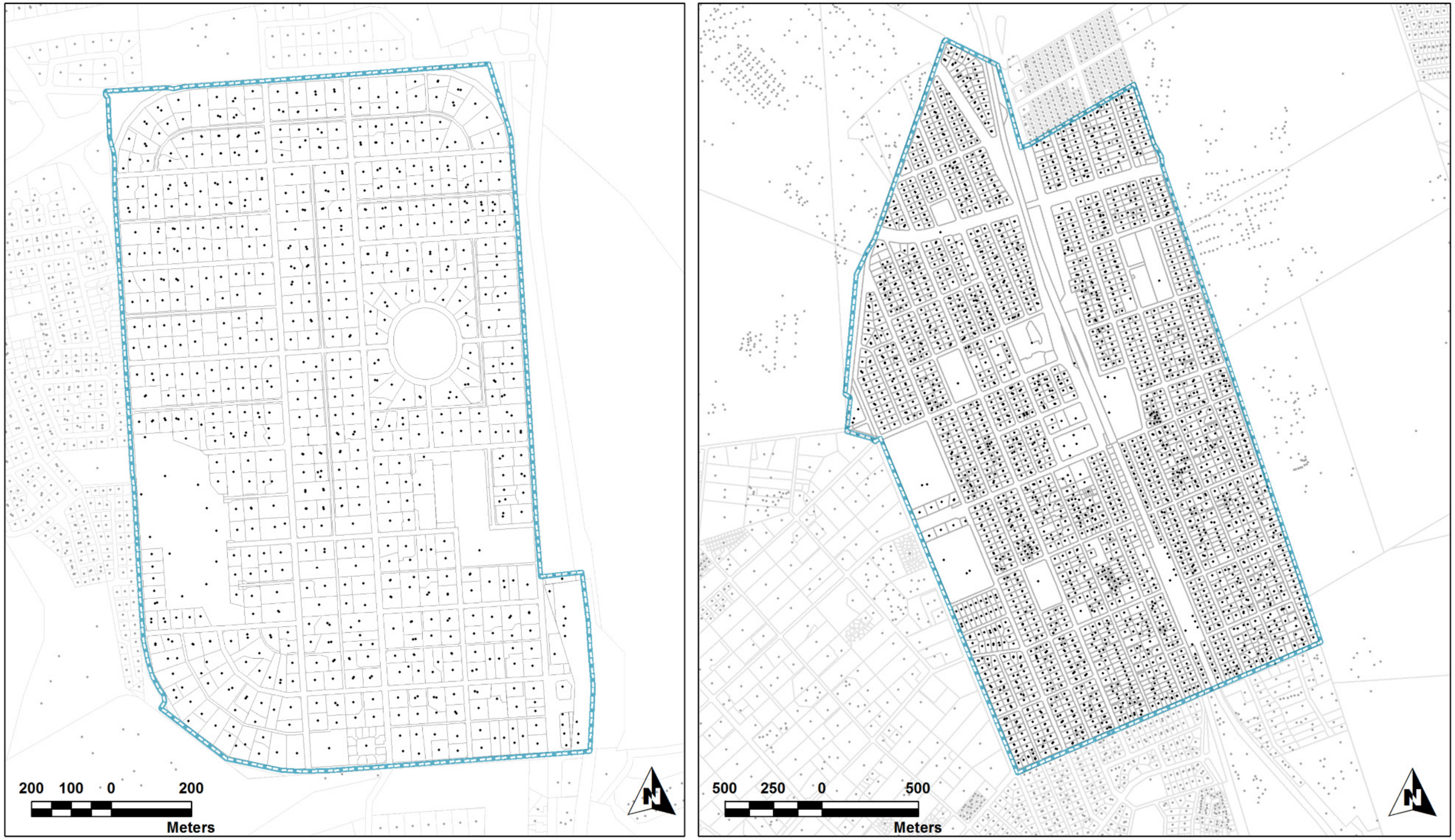
Map indicating the buildings of Irene (left) and Lyttelton (right). Each point represents a building

Buildings (Source ESKOM SPOT Building Count 2012)



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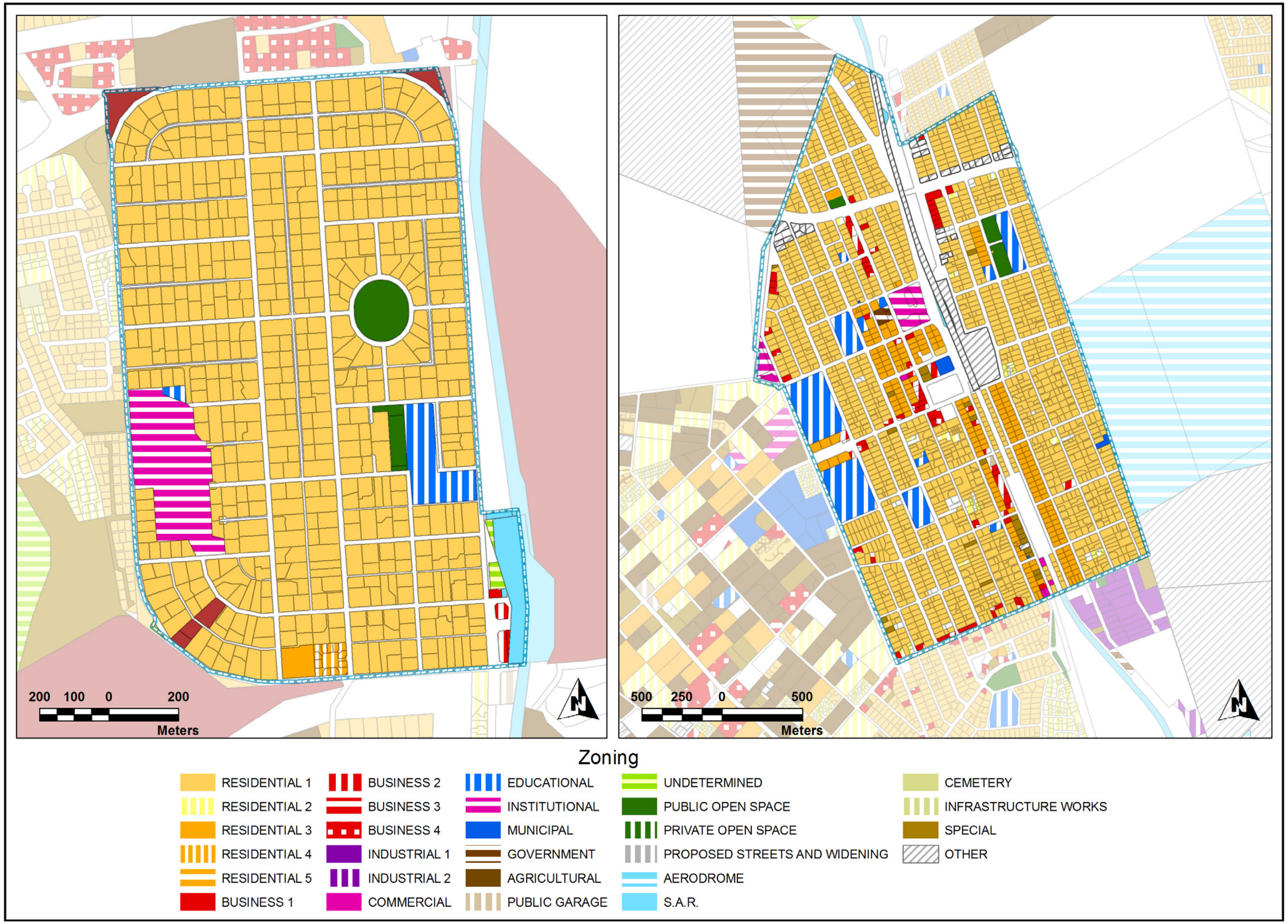
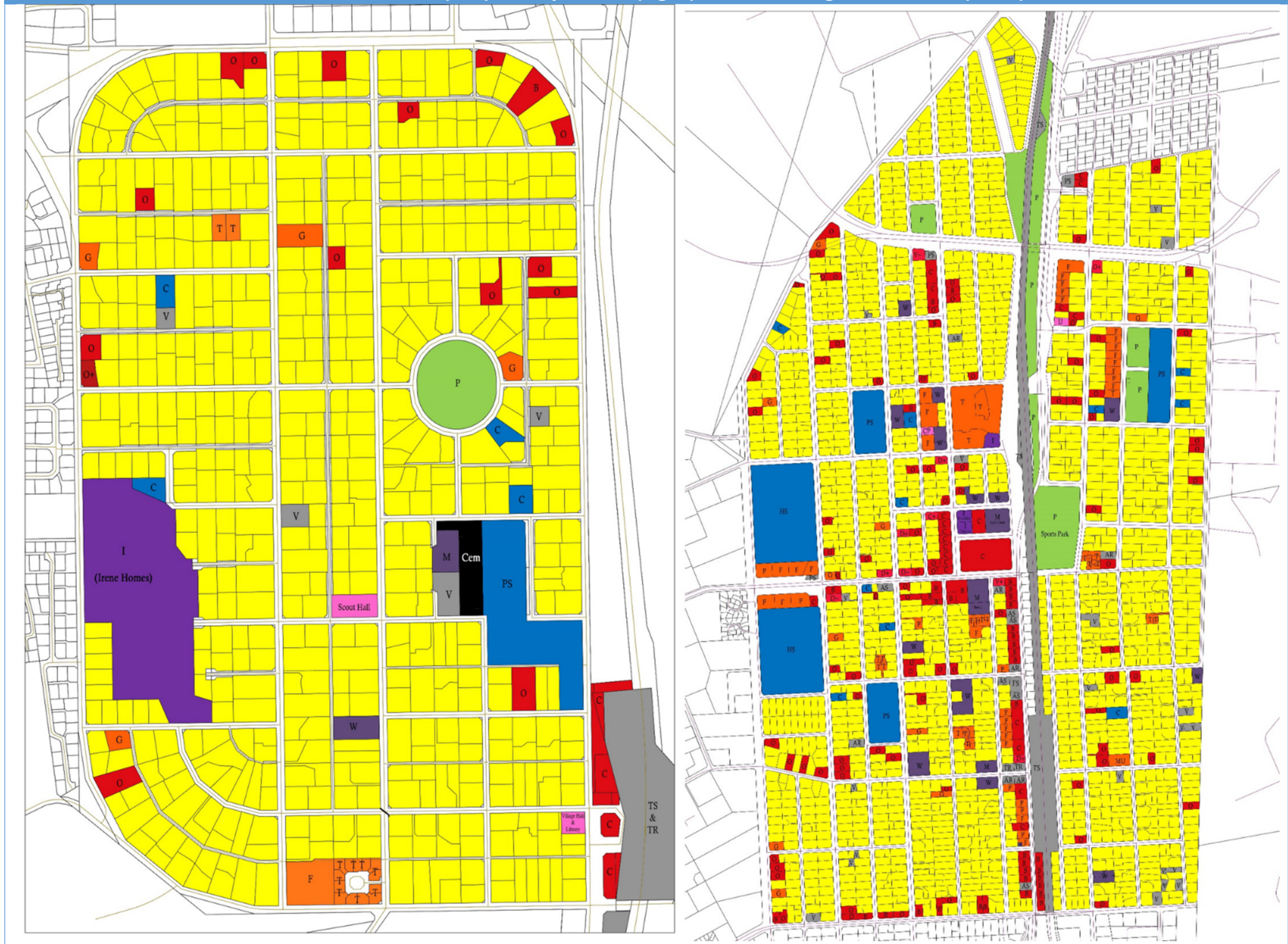
Land use zoning map of Irene (left) and Lyttelton (right) for 2013.

Zoning of Irene (left) and Lyttelton (right). Data source: City of Tshwane (2013)



Land use map of Irene (left) and Lyttelton (right). The land use survey was conducted in 2011

Land use of Irene (left) and Lyttelton (right) in 2011. Image source Nel (2011)



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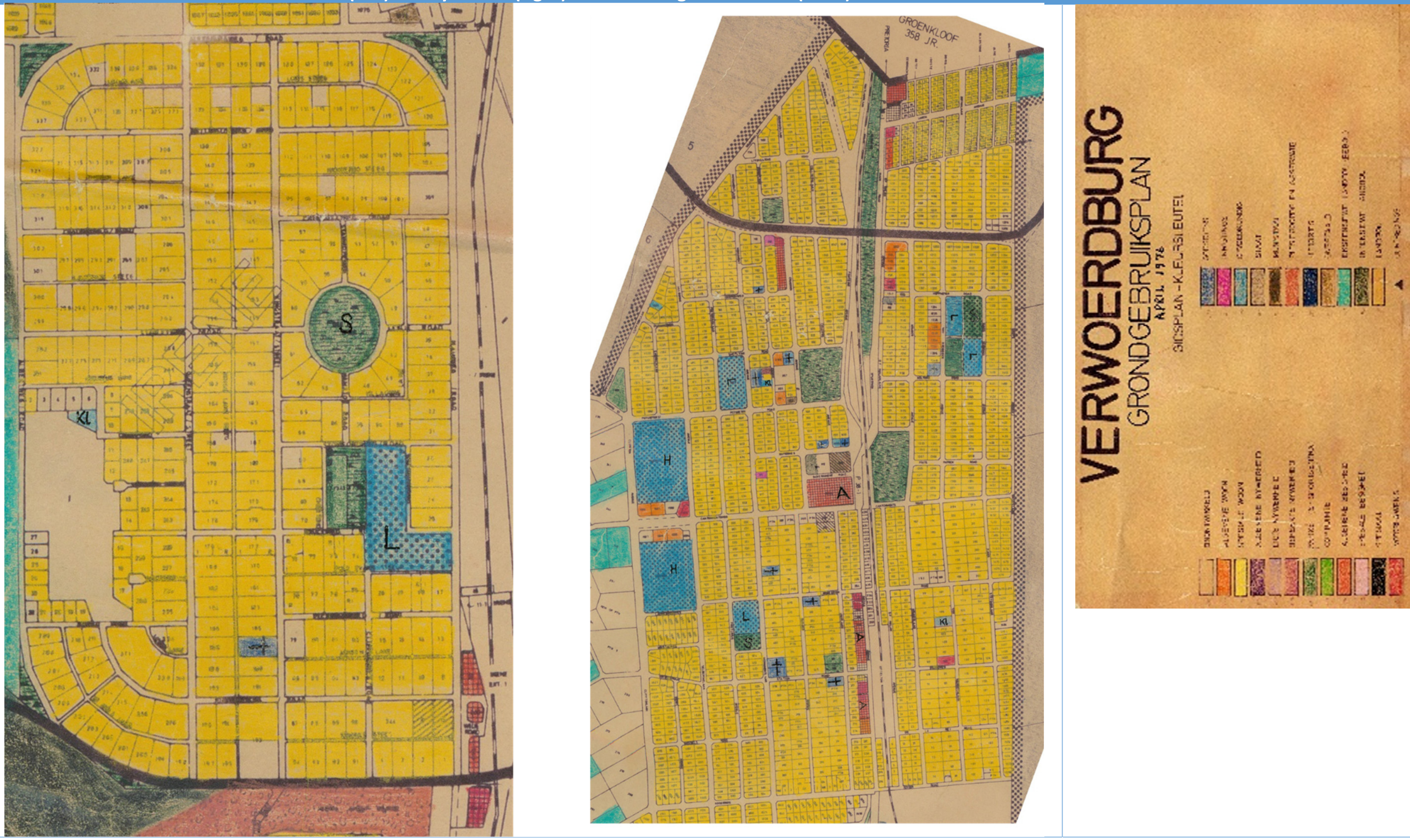
Land use map of Irene (left) and Lyttelton (right). The land use survey was conducted in 1976

Land use of Irene (left) and Lyttelton (right) in 1976. Image source Nel (2011)



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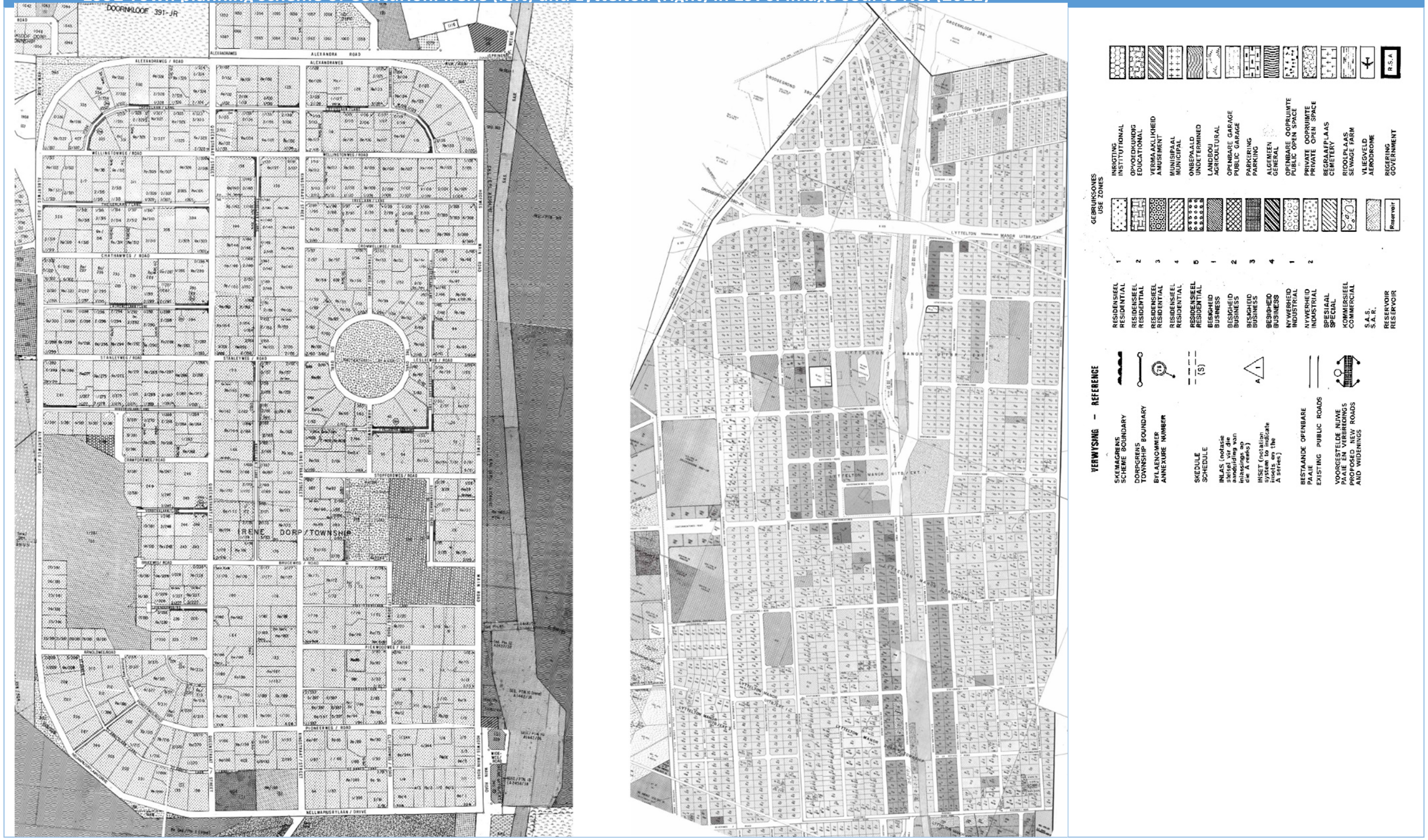
1992 Town planning scheme of Centurion with the land uses for Irene (left) and Lyttelton (right

1992 Town planning scheme of Centurion. Irene (left) and Lyttelton (right) in 1976. Image source Nel (2011)



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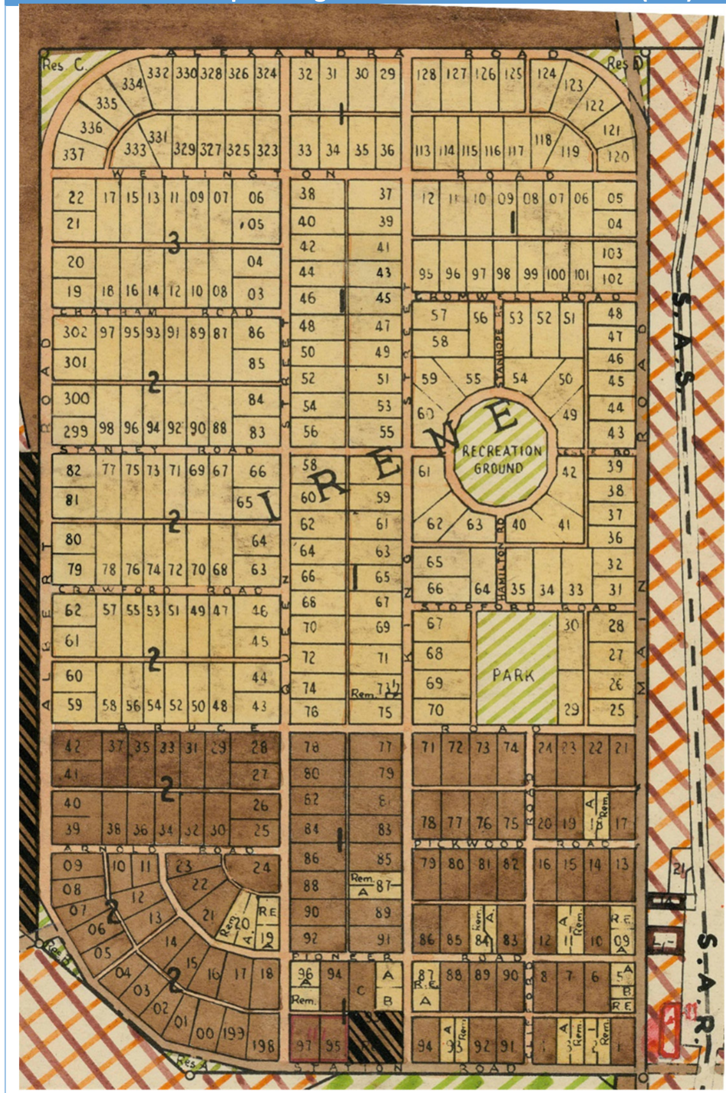
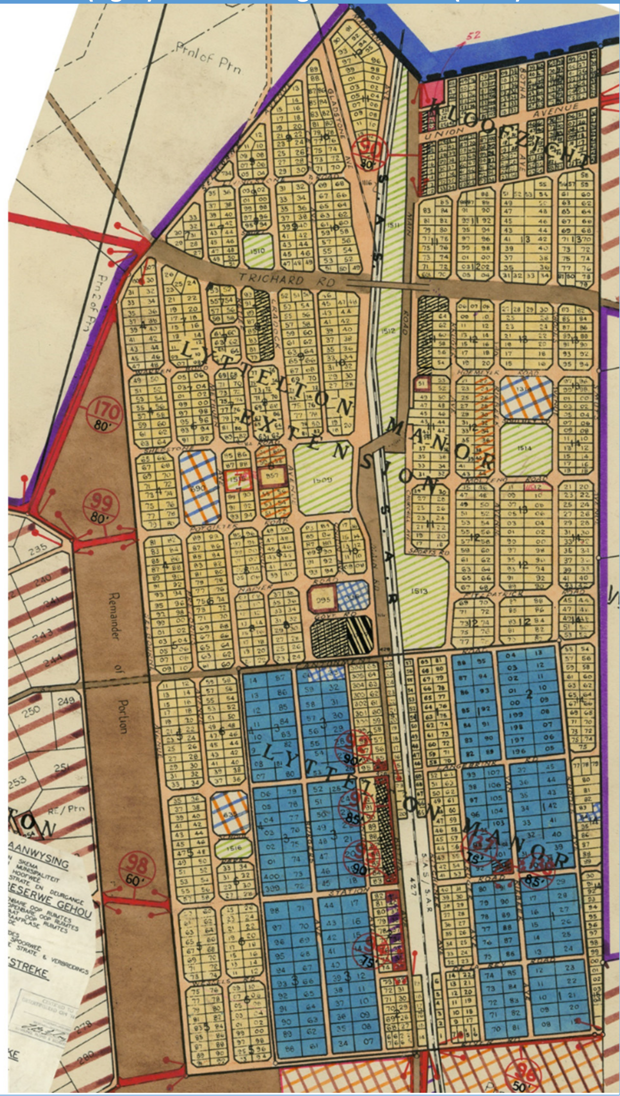
1992 Town planning scheme of Centurion with the land uses for Irene (left) and Lyttelton (right

1992 Town planning scheme of Centurion. Irene (left) and Lyttelton (right) in 1976. Image source Nel (2011)





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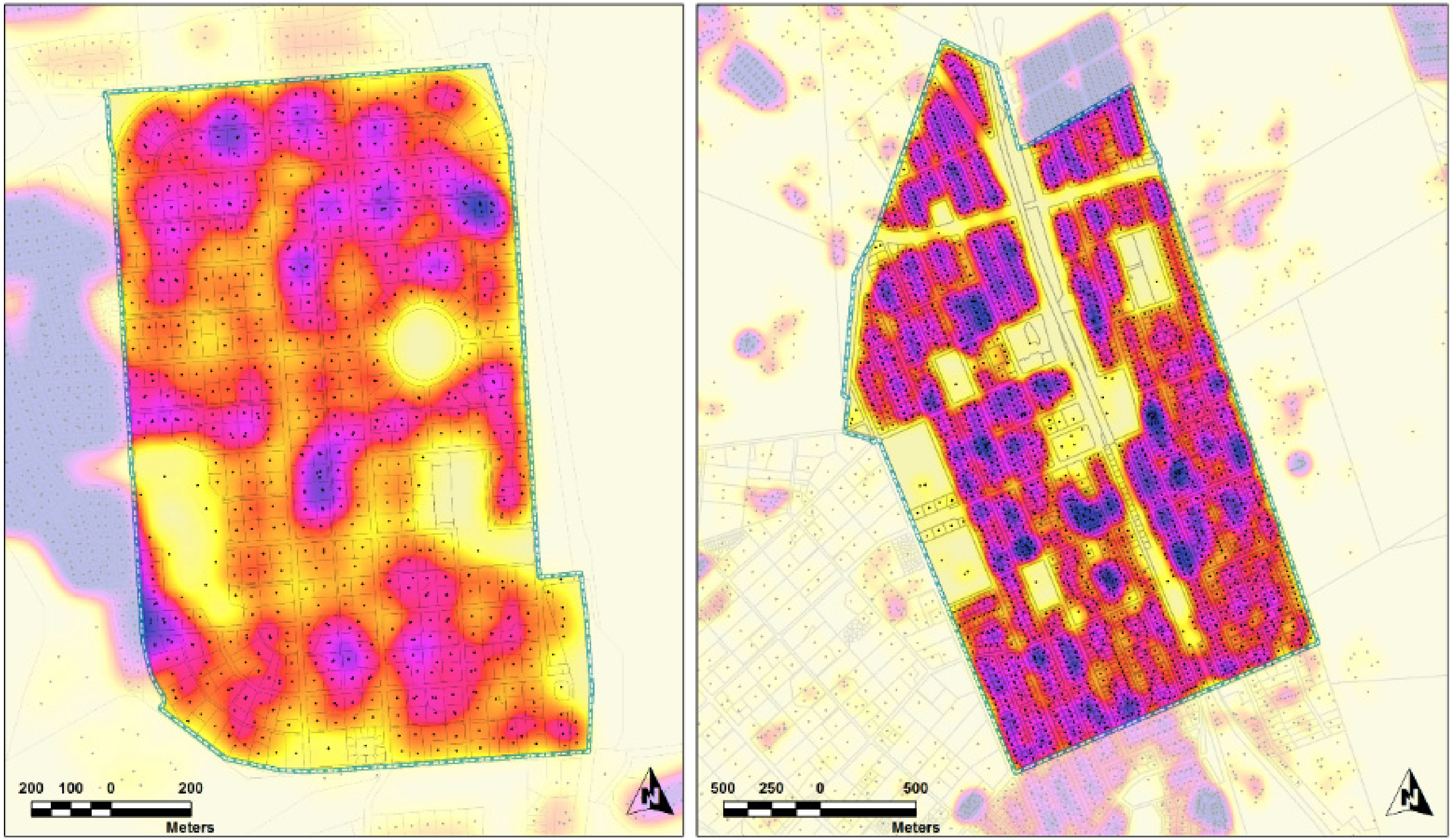
Building 100m kernel densities of Irene (left) and Lyttelton (right). Kernel densities are a statistical tool used calculate the density of features (i.e. buildings) in neighbourhood around those features with in a particular distance. For maps below it indicates the number of buildings that are with a particular distance from each other within an area (i.e. 10 buildings per 100m radius per km²)

Kernel Densities: 100m (Densities derived from ESKOM SPOT Building Count 2012 using ArcGIS kernel density function)



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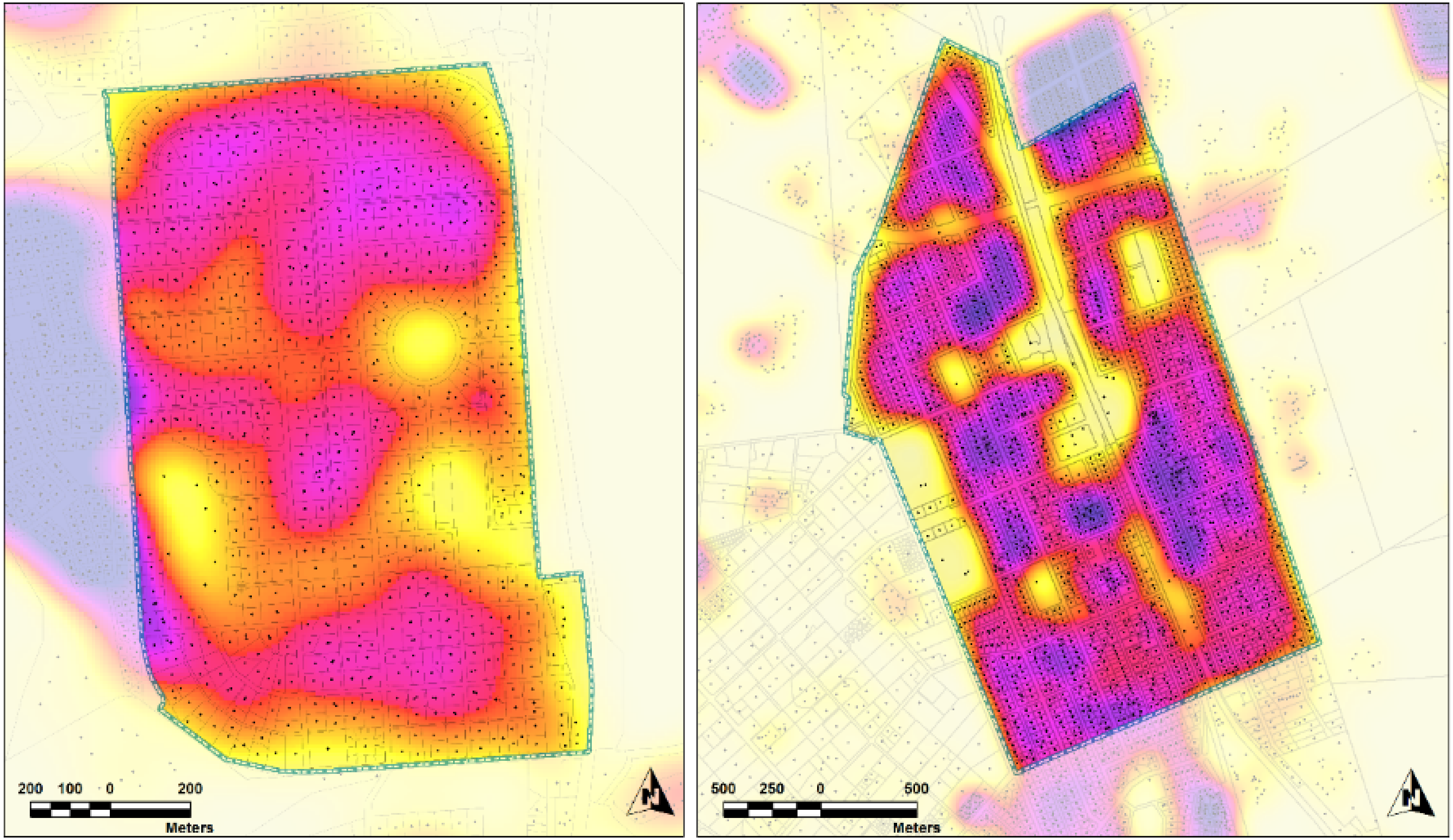
Kernel Densities: 200m (Densities derived from ESKOM SPOT Building Count 2012 using ArcGIS kernel density function)



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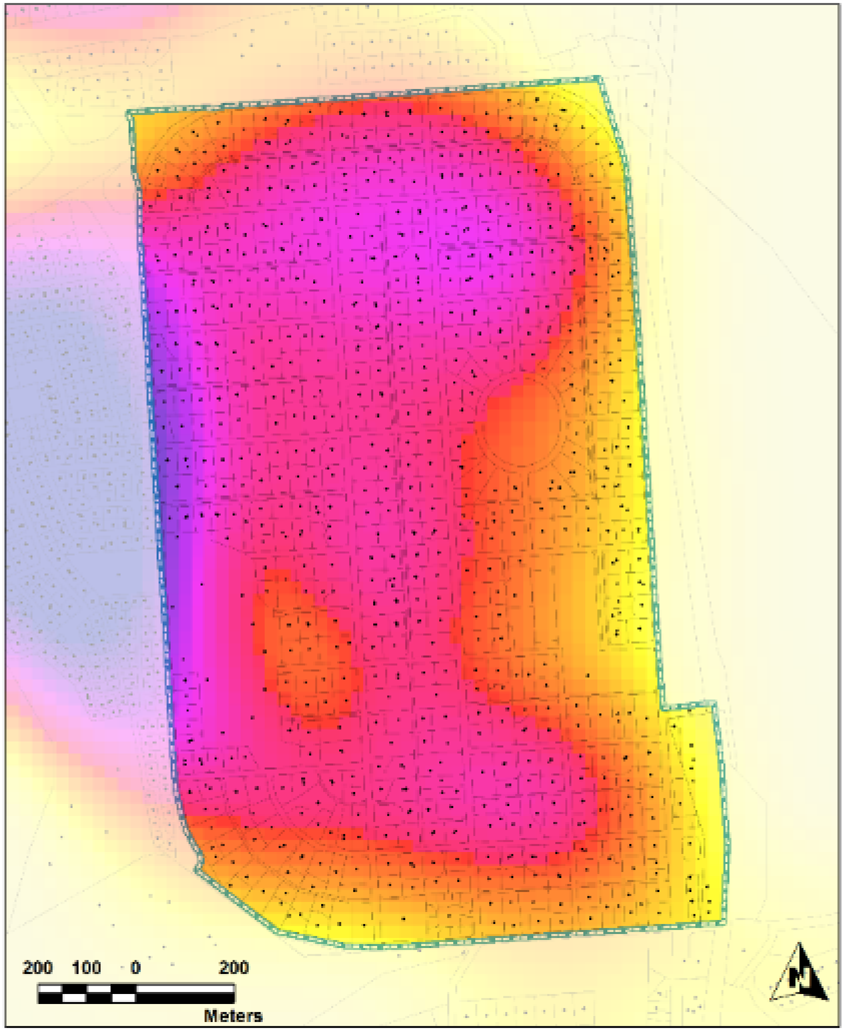
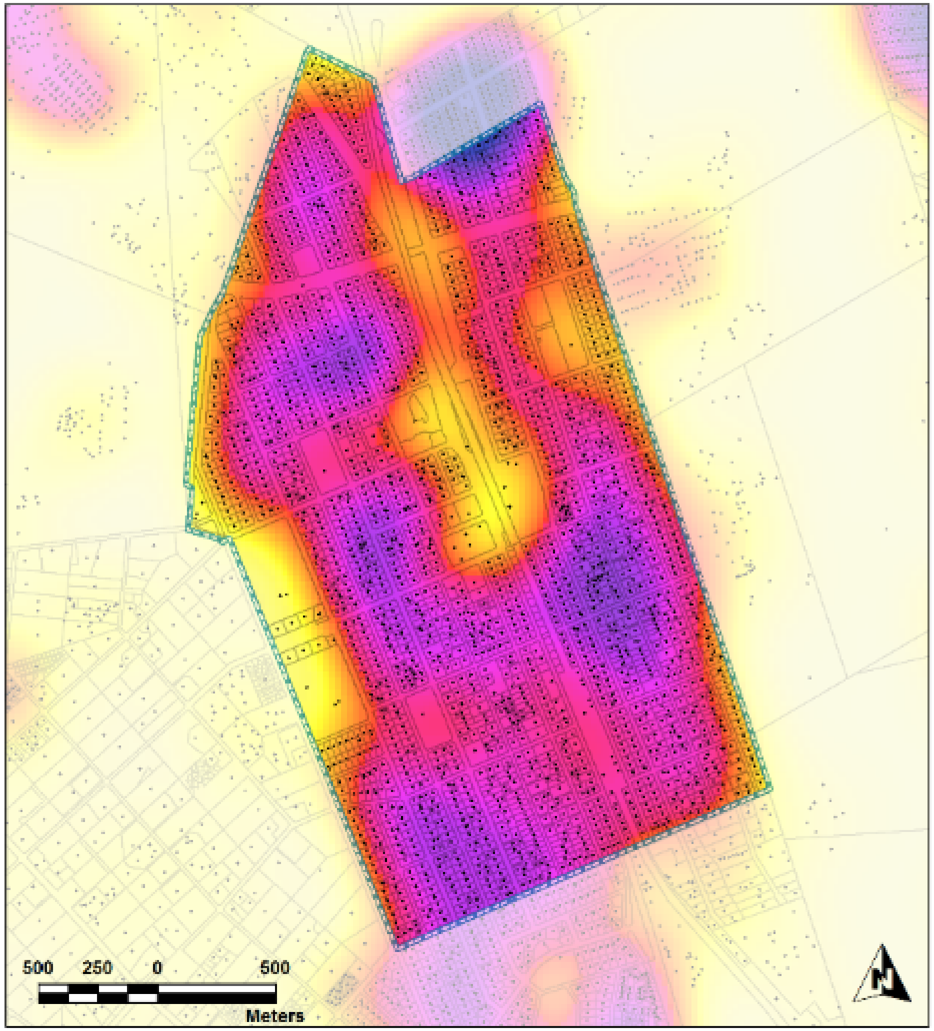
Kernel Densities: 400m (Densities derived from ESKOM SPOT Building Count 2012 using ArcGIS kernel density function)





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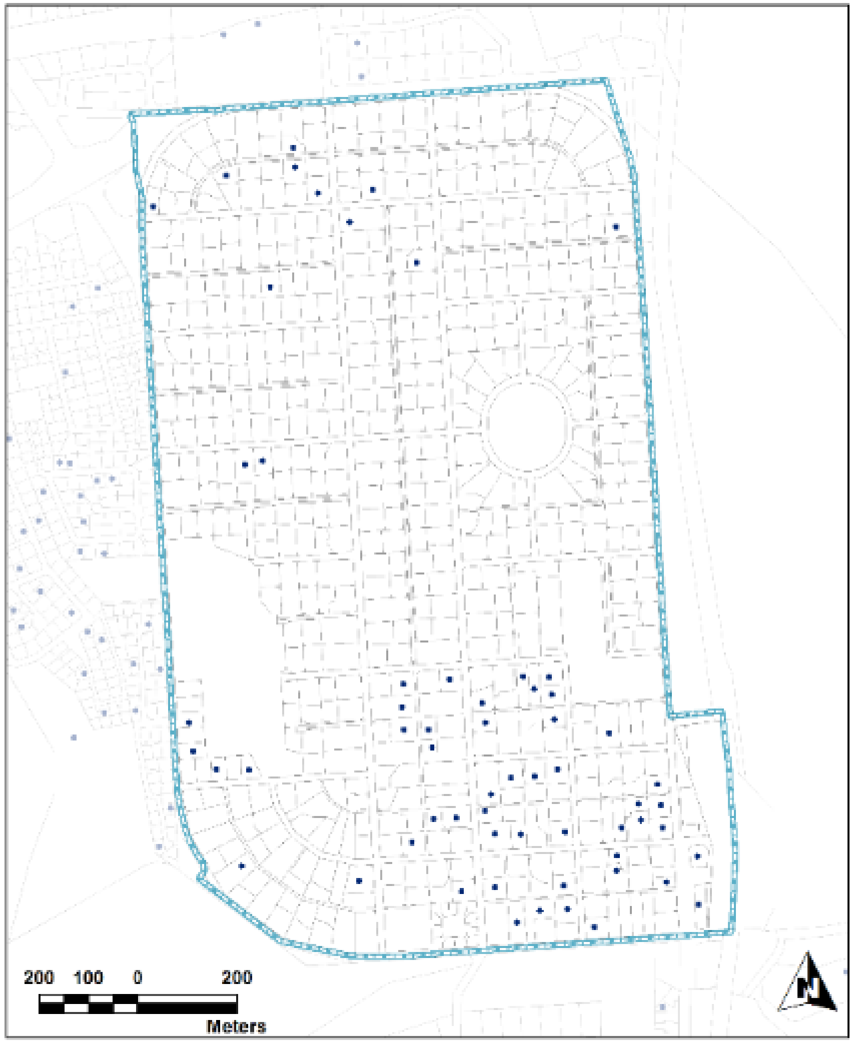
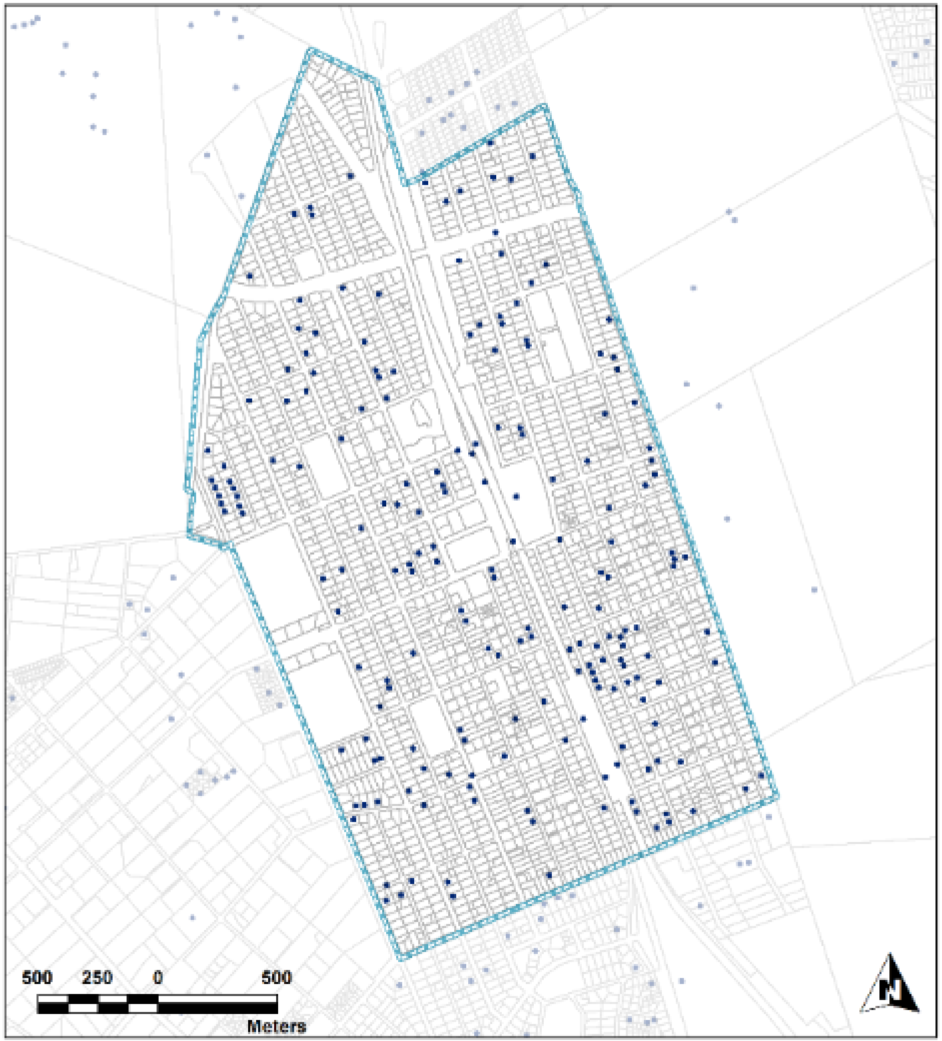
Non-residential buildings (point) of Irene (left) and Lyttelton (right).

Non-residential buildings (Source: Statistics South Africa Dwellingframe 2011)





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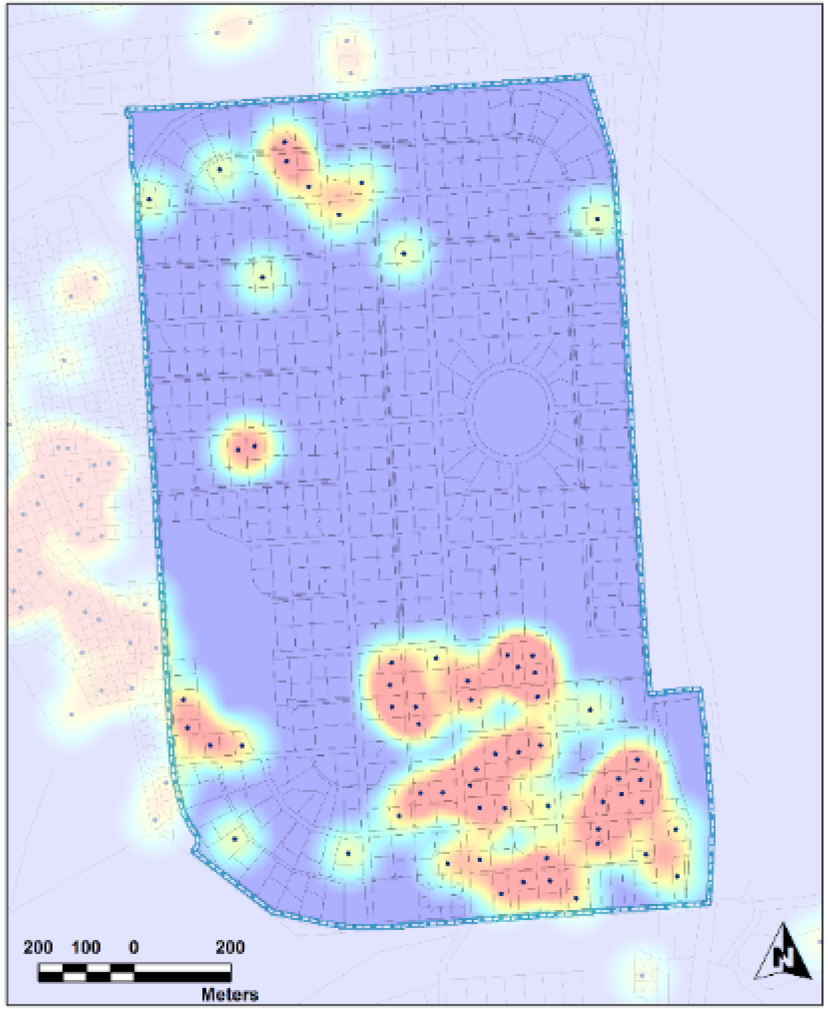
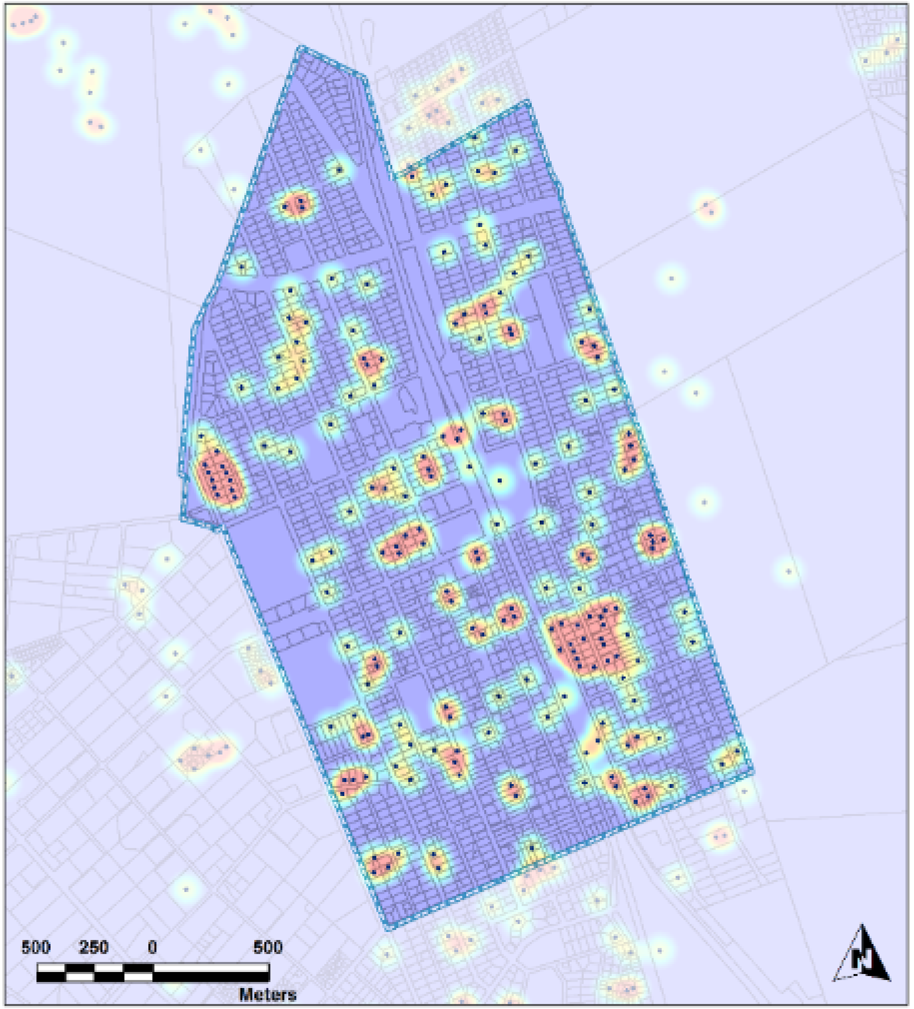
Kernel densities of non-residential buildings (point) for Irene (left) and Lyttelton (right).

Kernel Densities of non-residential buildings: 100m (Densities Statistics South Africa Dwellingframe 2011 using ArcGIS kernel density function)





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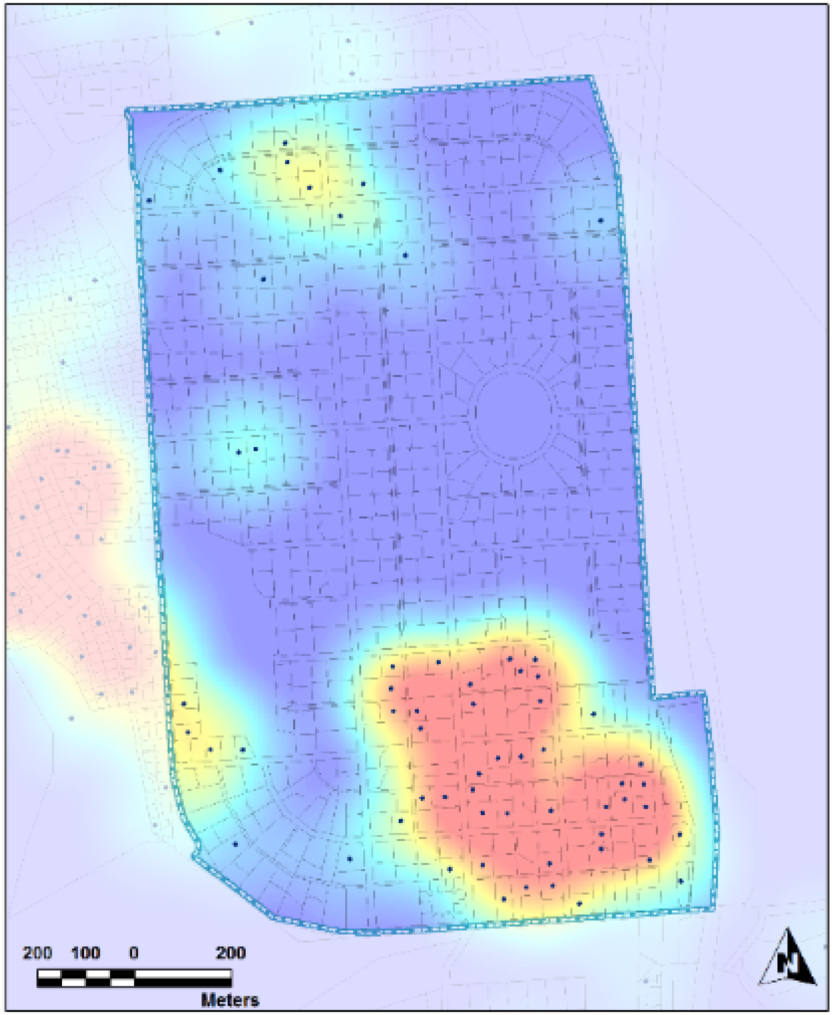
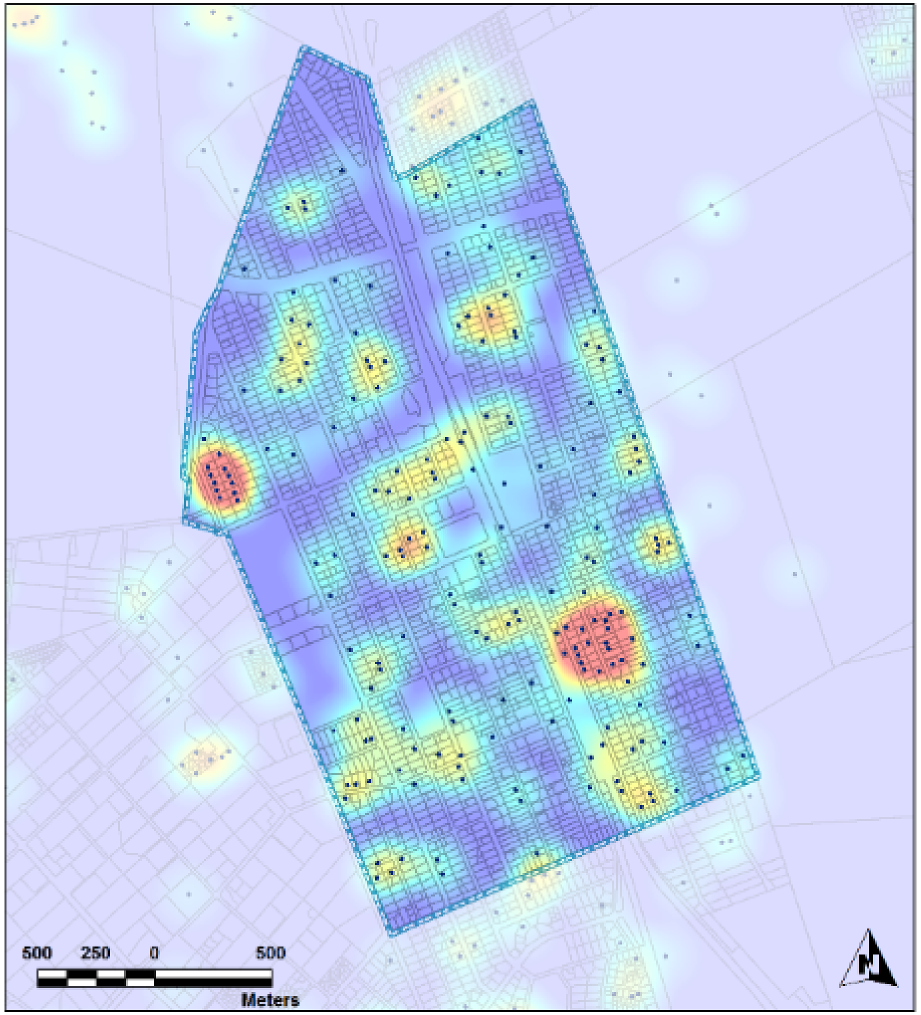
Kernel Densities of non-residential buildings: 200m (Densities Statistics South Africa Dwellingframe 2011 using ArcGIS kernel density function)





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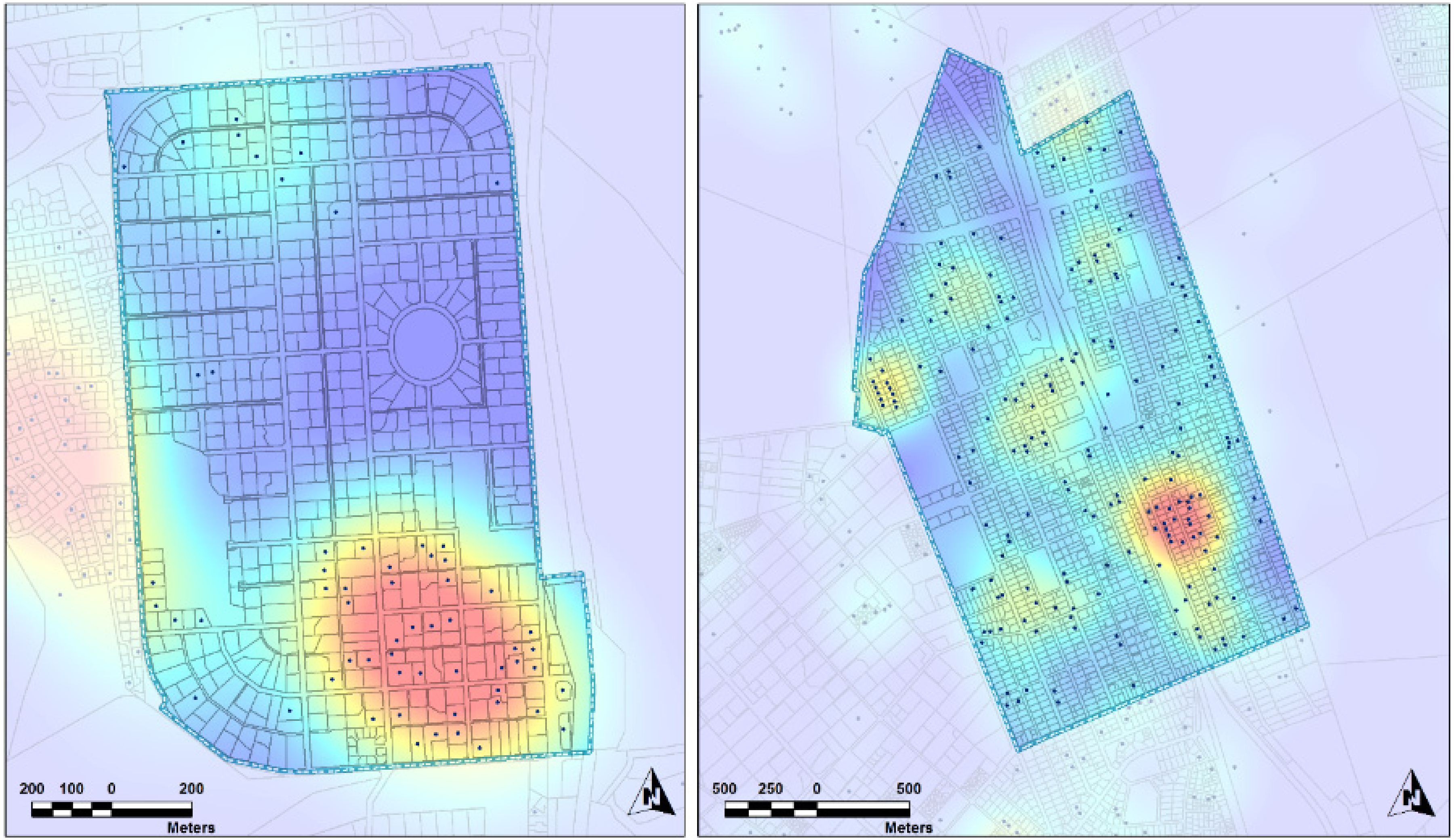
Kernel Densities of non-residential buildings: 400m (Densities Statistics South Africa Dwellingframe 2011 using ArcGIS kernel density function)



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Annexure 6. Indicators and measurements of urban form

A list of indicators and measurements for the elements of urban form. Adapted from Dempsey et al. (2010).

Indicators of density

Measurement	Description	Examples of aspects/features measured
Gross Density (City)	The ratio of persons, households, or dwelling units to the entire area of the city regardless of land use.	Total city population No. of households No. of dwellings City area
Gross Density (Neighbourhood)	Number of persons, households, or dwelling units per hectare of the total neighbourhood area.	Total population No. of households No. of dwellings Case study area
Gross Residential Density (Sub-area)	Number of persons, households, or dwelling units per hectare of the total sub-area area.	Total population No. of households No. of dwellings Sub-area
Net Residential Density (Neighbourhood)	Number of persons, households or dwellings per hectare of the total land area devoted to residential land use.	Total population No. of households No. of dwellings Total residential land area
Net Residential Density (Sub-area)	Number of persons, households or dwellings per hectare of the total land area devoted to residential land use within the sub-area.	Total population No. of households No. of dwellings Total residential land area
Net Residential Density (Street & Plot)	Number of dwellings per plot.	No. of dwellings per plot Plot area
Floor Area Ratio (Neighbourhood & Sub-area)	Ratio of floor area to site area.	Floor area (of each building) No. of storeys Site area (of each plot)
Coverage Ratio (Neighbourhood & Sub-area)	Ratio of building footprint to site area.	Building footprint (each building) Site area (of each plot)

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Indicators of Land Use

Measurement	Description	Examples of aspects/features measured
Residential land use (Individual dwellings)	Residential, institutional and communal accommodation	Sheltered accommodation Care homes University halls of residence
Commercial and retail land use (Individual buildings)	Properties housing all commercial uses	Retails & Supermarkets Shops Storage & Warehouses Restaurants/cafés
Offices (Individual buildings)	Office space	Business parks Banks and building societies Other offices
Industrial (Individual buildings)	Industrial properties including industrial storage and warehouses	Factories/Workshops Industrial storage facilities (depots etc.)
Community Buildings (Individual buildings)	Buildings used for community purposes including: educational health community services	Primary schools Health centres and GPs Hospitals Community centres Places of worship Police stations
Leisure and recreational Buildings (Individual buildings)	Buildings used for leisure and recreational purposes	Museums Libraries Cinemas Indoor sports facilities
Outdoor Recreation (Individual spaces)	Outdoor amenity and open spaces	Football pitches Golf courses Sports grounds Allotments
Other public green space (Individual spaces)	Spaces of grassland, woodland etc.	Woodland Heathland
Previously developed land (Individual spaces)	Previously developed land which is or was occupied by a building or other permanent structure	Derelict land Vacant land
Mixed use (Individual buildings)	Buildings with multiple land uses	– Vertical mixed uses (flats above shops/offices above commercial etc.)

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Indicators of accessibility

Measurement	Description	Examples of aspects/features measured
Public transport infrastructure (Street)	Location of public transport features	Location of bus/tram stops Bus/tram routes Frequency of services
Private transport infrastructure (Street)	Location of private transport features (i.e. parking)	Location of off-street parking and types Location of on-street parking and types
Pedestrian/cycling infrastructure (Street)	Location of (cycle) paths/alleyways/ underpasses etc.	– Location of routes inaccessible to motorized transport
Road management (Street)	Route management	One-way systems Traffic management Speed restrictions
Journey time/distance (Individual buildings)	Journey to work/other services etc. in terms of time and distance	Trip origin Trip destination

Indicators of housing/building characteristics

Measurement	Description	Examples of aspects/features measured
Housing type (Individual buildings)	Predominant housing type per street with exceptions marked	Detached housing Semi-detached housing Terraced housing Tenements Flats/apartments
Housing characteristics (Individual buildings)	Characteristics of individual dwellings	Lowest level of living accommodation Access to garden Number of bedrooms Condition of building
Building type (Individual buildings)	Building type according to land use categories	Commercial buildings Offices Community buildings
Street characteristics (Street)	Level of maintenance	Extent of litter Instances of graffiti Instances of vandalism Instances of no street lighting

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Annexure 7. Changes in Irene, Lyttelton and the lager scales

Summary of changes in Irene and Lyttelton as well as key world events that impacted on the two neighbourhoods. This was done in terms of social, economic, institutional and spatial changes.

	Size of Change	Pre-1900		1900s		1910s		1920s		1930s		1940s		1950s		1960s		1970s		1980s		1990s		2000s	
		What	Type	What	Type	What	Type	What	Type	What	Type	What	Type	What	Type	What	Type	What	Type	What	Type	What	Type	What	Type
Irene	Small			Irene Homes Opens	P, S	Irene golf course created	P			Train line connecting Pretoria and Johannesburg electrified	I, S	Irene under jurisdiction of Peri-Urban Areas Health Board	I			Station road renamed to Nallmapius	S	Geological survey	I	proposed reopening of police station	S, I				
Irene	Small			Police station Opened	P, S, I											Irene village absorbed into Lyttelton municipality	I	All the roads in Irene tarred	P	Tarring of Lanes in Irene	P				
Irene	Small															Irene Village Hall & Library relocated	P, S			construction of Village Lane	P				
Irene	Small															Most of the erven have houses; majority of principal roads are tarred	P								
Irene	Medium							Irene Library and village hall opened	P, S, I	New Post office	P, I, S	Start tarring of roads	P	The Oval is started	P, S	'Irene stone walls' (due to increased crime)	P, S	Irene Village Association petition road works	S	Investigation to become a free settlement area (under the Free Settlement Areas Act of 1988)	S				
Irene	Medium							Electric lights (powered by steam engine)	P, S	Dual train lines are laid down	P, I, S	piped water from Rand Water Board	P, I			Irene police station closed	I, S	Road construction projects underway within the areas surrounding Irene	I, P	Irene Village Association petition to prevent restaurant at Smuts House	S				
Irene	Large	train station	P	Irene Primary is reopened (bilingual school	P, S					Electricity from the Pretoria Municipality	I	Irene Village Association formed	S	Irene X1 established (retail purpose)	E, P	rerouting of planned K 54 due to Irene Village Association	I, S	Dooringkoof Primary is opened and Irene Primary becomes an English school	S			Neighbourhood Watch started	S	Closing off and limiting of access into the Irene Village	S, E, I
Irene	Large	Irene dairy farm	P, E	Irene Is Established	P, S					Train station moved North	I, P											Opening of Cornwall Hill Country Estate & Cornwall Hill Collage	P, S, E		
Irene	Large																	Opening of lanes for subdivisions in Irene	I, S, E, P						

* Size of change is determined by the impact the that change has/had on the areas today

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Lyttelton	Size of Change	Pre-1900	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s
		Change	Change	Change	Change	Change	Change	Change	Change	Change	Change	Change	Change
	Small		Electricity from Pretoria power station Limited water supplied from borehole		Fall of the Rand after WWI	Train line connecting Pretoria and Johannesburg electrified		Many streets names changed in Lyttelton	Lyttelton Municipality was renamed to Verwoerdburg	Additional tarring of roads, installation of storm water management and more street lighting	Home affairs office is opened in Lyttelton Two boreholes to supplement water supply	Lyttelton Urban Renewal Project let to the widening of River Rd	
	Medium					Dual train lines are laid down	Village Committee is created Post offic opens End of the Second World War	First planning scheme for Lyttelton	Laerskool Fleur opened New dual carriage way proposed along Botha	Sinkholes due to dolimight in area hinder some development in the areas (mandatory for geological surveys and dolomite stabilisation for new townships in area)	Aging of residents led to many subdivisions of erfs Widening of Botha affected access to commercial activities on the east side of Botha Ave due to no direct access redevelopment of a park to	Civil servants offered voluntary severance packages, leading to a mass exit of civil servants many of them started small businesses within the area 1st democratic elections	Completion of the commercial development along Botha ave Geologists reduce the allowed density if area due to dolomite
	Large	Lyttelton train Station	Lyttelton Manor proclaimed				First primary school (Laerskool Louis Leipoldt) Lyttelton gets water Lyttelton X1 proclaimed	Lyttelton Primary opened Hoërskool Laneghoven opened	Lyttelton Manor High school opens Lyttelton Shopping centre built	Lyttelton Manor Industrial is established Large scale extensions to Lyttelton Engineering works as part of the ARMCOR development	Urban renewal/ Subdivision policy of residential 1 erven in Lyttelton; Residents against idea of 'small street access' & opt for panhandle access Construction & widening of Cantonments, Botha Ave & Bridge over Botha	Due to the demand for schools there were many younger people moving into the area New town planning scheme (allowed for second dwellings, a site development plan, as well as home-based occupations	

* Size of change is determined by the impact the that change has/had on the areas
* Type of change: P = Physical/ Spatial ; S = Social ; E = Economic; I = Institutional

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Spatial Scale	Pre-1900	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s
City					Government builds the Old Pretoria road & Rietvlei dam constructed (to help alleviate the economic situation in area)			Opening of Ben Schoeman highway		First shops open in Verwoerdburgstad Town Council commissions two boreholes to supplement its water supply	New town planning scheme (allowed for second dwellings, a site development plan, as well as home-based occupations from dwelling	
National	Anglo Boer	End of Anglo Boer	Union of South Africa established	The Native Affairs Act Fall of the Rand after WWI		National Party elected to government	Apartheid Policies are enacted	Economic boom	Oil Crisis Soweto riots and Banning of the ANC	Defence force boom Economic decline Drought	Unbanning of the ANC DFA 1995 Abolition of Apartheid legislation 1st democratic elections	Global recession and a slowing down of most development
International			First World War		Second World War Great Depression	End of the Second World War						

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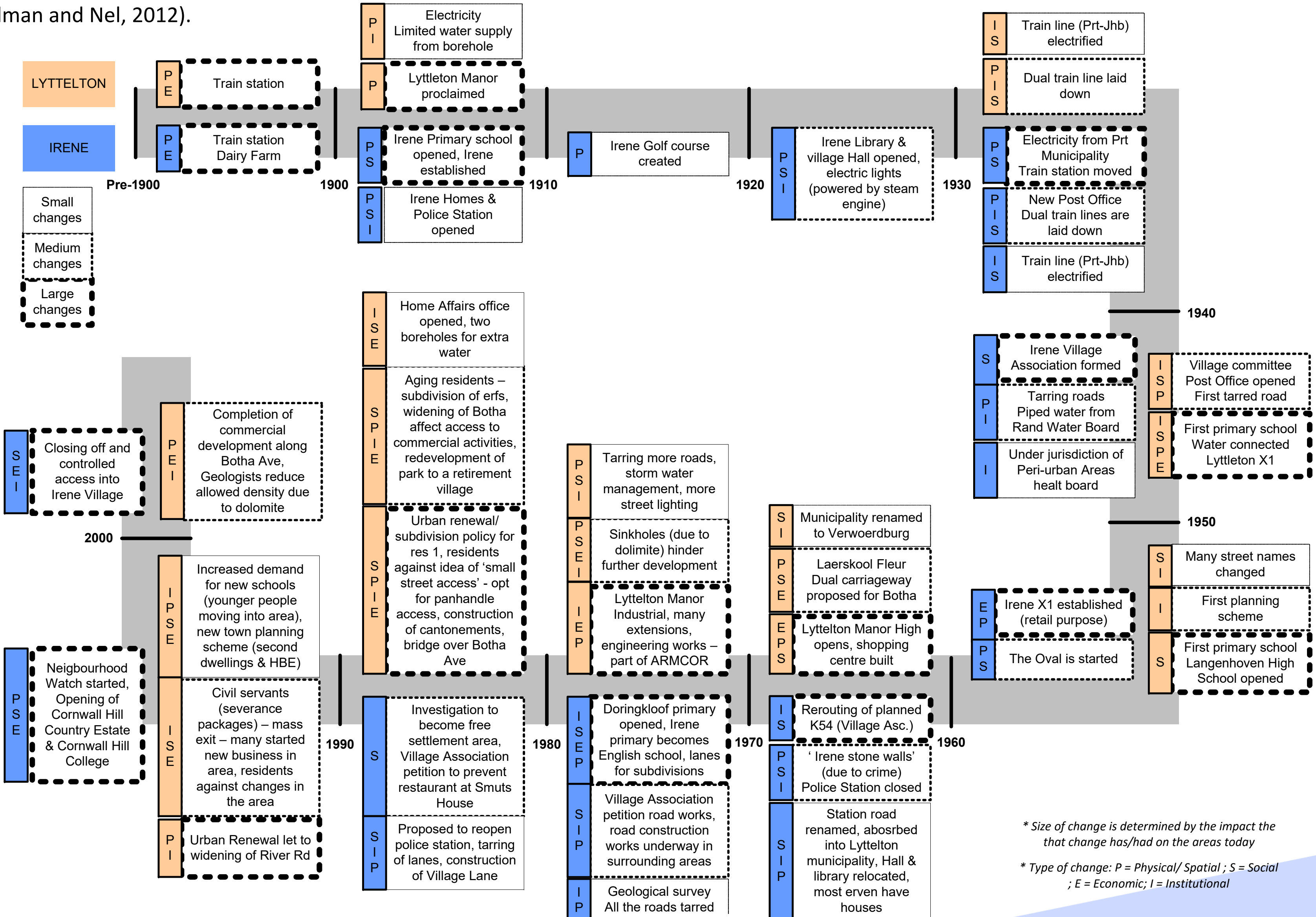
Annexure 8. Summary of the changes in Irene, Lyttelton with magnitude of changes

Summary of the changes in Irene and Lyttelton which have been broken down into the type of change as well as the magnitude of the impact of that change (Landman and Nel, 2012).



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